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A SIMULATION STUDY OF THE CONTROL PROBLEMS ENCOUNTERED WHEN DOCKING THE LEM WITH THE COMMAND MODULE-SERVICE MODULE COMBINATION

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Report No. NA63H-82

A SIMULATION STUDY OF THE CONTROL PROBLEMS ENCOUNTERED WHEN DOCKING THE LEM WITH THE COMMAND MODULE-SERVICE MODULE COMBINATION

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ABSTRACT

This report presents the results of a lunar-orbital-docking simulation study performed under contract to the NASA Manned Spacecraft Center. The handling qualities problems associated with the lunar orbital docking task were studied utilizing three modes of attitude control for an "on-off" thrust system. The attitude control modes consisted of the rate command, rate command with attitude hold, and the acceleration command systems. Translational control was provided exclusively by an "on-off" acceleration system. The effects of thrust level, control system deadbands, maximum slewing rate capabilities, and cross-coupling were evaluated. In addition to the translational and attitude control studies, the usefulness of visual displays and the effect on performance of extreme initial conditions were investigated. The study was performed on a six-degree-of-freedom, visual fixed base simulator in conjunction with the 1/10 scale model of the Apollo command module and the existing lunar-excursion-module cockpit. The study was confined to the final 200 feet of the docking maneuver.

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NOMENCLATURE

a_o	attitude feed-back gain
a_1	rate feed-back gain, sec
I	denotes inertia term
I_{xx}	moment of inertia about x-axis, slug - ft^2
I_{yy}	moment of inertia about y-axis, slug - ft^2
I_{zz}	moment of inertia about z-axis, slug - ft^2
K	forward loop gain, deg/sec/inch
l_θ	pitch moment arm, feet
l_ϕ	roll moment arm, feet
l_ψ	yaw moment arm, feet
m	mass, slug
M	denotes total moment
p	rolling angular velocity, deg/sec
q	pitching angular velocity, deg/sec
r	yawing angular velocity, deg/sec
rms	root-mean-square
s	Laplace operator
T_x	thrust in x-direction, lb
T_y	thrust in y-direction, lb
T_z	thrust in z-direction, lb
T_θ	thrust for pitch, lb
T_ϕ	thrust for roll, lb
T_ψ	thrust for yaw, lb

NOMENCLATURE (Cont'd)

δ_p	stick deflection for roll, inches
δ_q	stick deflection for pitch, inches
δ_r	stick deflection for yaw, inches
ΔT	increment in thrust, lb
ΔZ	vertical c.g. displacement from thruster plane (positive downward), ft.
ϵ	error signal for attitude control system, deg
θ	pitch angle, deg
ϕ	bank angle, deg
ψ	yaw angle, deg

Subscripts:

o	initial condition
c	command
a	actual

INTRODUCTION

The success or failure of the lunar orbital rendezvous concept for manned exploration of the moon lies largely in the ability of the LEM's pilots to make a successful rendezvous and subsequently dock with the moon-orbiting command module. It therefore becomes necessary to define detailed pilot handling requirements for the final stages of the docking maneuver.

It was the purpose of this study to evaluate the handling qualities problems specifically associated with the lunar orbital docking task and recommend, as a result of these studies, the following:satisfactory translational thrust level, satisfactory attitude control characteristics, and beneficial display and visual aids.

The control system was mechanized to provide three modes of attitude control. These modes consisted of the rate command, the rate command attitude-hold, and the acceleration command. The effects of thrust level, system deadband, maximum slewing rate capabilities, and control cross-coupling were studied in order to establish pilot opinion ratings and performance as related to the system characteristics. In addition, to the translational and attitude control studies, the usefulness of visual aids and the effect on performance of extreme initial conditions were investigated. The thrust system worked exclusively on an "on-off" basis.

To investigate the control problems encountered during the final 200 feet of docking maneuver, NAA Columbus employed the on-site six-

degree-of-freedom visual flight simulator in conjunction with the 1/10 scale model of the Apollo command module and the existing lunar-excursion-module cockpit.

SIMULATOR DESCRIPTION

The six-degree-of-freedom visual flight simulator consisted of the following components: computer, console and monitor, TV camera, camera transport, model of Apollo command module, lunar-excursion-module cockpit, TV projector, star projector, and the projection screen. A schematic lay-out of these components is presented in Figure 1.

The lunar cockpit (Figure 2) consisted of a functional instrument panel; system controllers; and an intercom system among the cockpit, the computer, and the monitor. Display instrumentation (Figure 3) consisted of an all-attitude indicator (AAI or 3 axis 8-ball) and a timer. Translational control of the on-off reaction jets was achieved by a three-axis microswitch controller (Figure 4) located on the left side of the pilot. The NASA 2-axis pencil type controller (Figure 4) was used for pitch and roll control and is a linear, spring-centered 3-inch stick with a $\pm$ 30° throw in pitch and a $\pm$ 20° throw in roll. Directional control was provided by spring-centered, foot operated treadles.

The program was mechanized in such a way that the pilot inputs to the control system were fed into the analog computer (Figure 5) which solved the equations of motion and in turn sent the vehicle response back to the TV camera rig (Figure 6) and the starfield projector rig. The TV projector provided a picture of this motion which was projected onto a 12 x 16 screen located 17 feet forward of the cockpit (Figures 7 through 9). The appropriate analog output signals were used also to drive the AAI. A flow diagram of the complete set-up is presented in Figure 10. The equations of motion used in the study and a drawing of the analog computer mechanization are presented in the Appendix.

PROGRAM DISCUSSION

General

The primary problem areas investigated were translational thrust levels, attitude control characteristics, cross-coupling effects, visual aids, and extreme initial conditions. A detailed study of a particular system was not feasible at this time since a definite system had not been established. Instead, a limited study was made of the most important parameter in each of the three different command modes involving attitude control.

The "on-off" reaction jet configuration consisted of four pairs of jets located symmetrically about the z-axis at each of four stations. The thrust system was mechanized to provide for two jets operating together in translation and two jets operating together to produce a couple for rotation. Each jet provided the same thrust level in an on-off manner. Thrust level, as referred to in this study, pertains to the thrust for each individual thruster.

The acceptability or unacceptability of certain conditions of characteristics, as determined by pilot opinion, was based on the standard Cooper pilot-rating scale. A pilot rating of 3.5 defined the boundary between satisfactory and acceptable, and a rating of 6.5 defined the boundary between acceptable and unacceptable (Table I).

Thrust Level Study

Due to the significant effect of the thrust level on the handling qualities and contact performance of the vehicle, a satisfactory thrust

level for each command mode was determined from pilot opinion ratings at the beginning of the study. It was necessary to obtain this satisfactory thrust level so that it would not bias the pilot evaluation of various control system characteristics later in the study.

During this phase of the study, the attitude control system was treated as an independent variable and nominal values were selected for such parameters as deadband, maximum slewing rate, system hysteresis, feedback gain, and cross-coupling. Exploratory runs were made prior to the beginning of the evaluation runs in order to determine which numbers would be satisfactory to use as nominal values.

Attitude Control Study

The effect of a particular system characteristic on pilot opinion ratings was investigated in each of the three modes of attitude control. This phase of the study utilized the previously selected satisfactory thrust level for each of the command modes.

The system characteristic studied for the rate command system (Figure 11) was the maximum slewing rate capability. This is most commonly referred to as the maximum rate a pilot can command with full stick throw. The pilots were required to fly and evaluate various maximum slewing rates which were varied systematically. The values studied were 5, 10, 15, 20 and 40 deg/sec. Conclusions relative to pilot desired stick sensitivities were to be obtained from this investigation.

The rate command attitude-hold mode (Figure 12) was studied utilizing the previously selected satisfactory stick sensitivity for the rate command mode. The parameter studied was the attitude deadband. Parameters such as system hysteresis, maximum slewing rate, and feedback gains were held constant. The system hysteresis in the attitude-hold mode was a function of the thrust level selected for this particular control mode. Four values of attitude deadband were investigated and varied from ± 0.5 to ± 4.0 degrees in multiples of two.

Pilot evaluation was made of the different attitude deadbands to determine what could be considered a tolerable level of attitude deviation for the system. Although a very narrow deadband would seem most desirable from the standpoint of holding commanded attitude, it may not prove to be the most economical fuel-wise. On the other hand, a large attitude deadband would result in the vehicle drifting to such large attitudes that the pilot could sense deviations and correct the attitude manually. This would be essentially the same system as the rate command mode.

No further parametric study was made of the open-loop acceleration command system (Figure 13) other than the thrust variation previously described. However, a minimum impulse provision (Figure 14) was incorporated into the acceleration system for attitude control to determine the suitability of using a thrust level of 100 pounds. This impulse provision provided for a selected impulse duration (e.g. .015 sec.) when the pilot moved the control stick beyond a certain percent (15) of the total stick deflection. In order to obtain another impulse it was necessary for the pilot to bring the stick

below the point of firing and again put it beyond 15% of the total stick throw. At no stick deflection could a continuous impulse be obtained. It should be noted that the thrust controller for translational control was not improvised to give a selected impulse. Due to the time restriction of the program, the minimum impulse was investigated in an exploratory manner and a very quick look was given to impulses of 7.5 and 15 milliseconds.

Cross-Coupling Effects

Two forms of cross-coupling were mechanized into the study. The first form resulted from an off-set in the center-of-gravity which caused a translational command to induce a rotational motion. The second form of cross-coupling resulted from asymmetric thrust levels on any pair of attitude thrusters which caused a rotational command to induce a translational motion.

In order to evaluate the influence of the cross-coupling due to c.g. offset, three values (1, 2, 4 ft.) of c.g. displacement (ΔZ) were investigated. These values were taken in the direction below the thruster plane.

Three different asymmetric thrust levels were studied to determine their influence on pilot opinion and performance. These values were 2.5% 5% and 10% thrust differentials. For example, a 100 pound thrust system would result in 110 lbs. of thrust on one jet and 90 lbs. on the other for a 10% differential.

These cross-coupling effects were studied in each of the three command modes previously selected by pilot opinion as having satisfactory control characteristics.

Visual Aids and Initial Conditions

During the previous studies the initial range, lateral displacement, and relative velocities were held constant. The only variables, as far as initial conditions were concerned, were the lateral and vertical locations. The pilot was placed in different quadrants but always at the same radial distance from the center. This made it necessary for the pilot to use a different series of inputs for each docking maneuver. In order to evaluate the effect of extreme initial conditions on performance, three different conditions were investigated for the optimum control characteristics for each of the three command modes.

Also during the previous studies the pilot was provided with a TV image, an all-attitude indicator, and a timer. To establish the usefulness of visual aids, the pilot was required to fly with the AAI inoperative and to make subsequent runs with a gun-sight-type visual aid. These runs were conducted for each of the three-command modes operating at their respective optimum levels.

STUDY PROCEDURE

The acceptability or unacceptability of various control system characteristics was based primarily on the pilot opinion ratings. The NASA Cooper scale (Table 1) was used as the standard for these ratings.

Prior to the production runs, each pilot was familiarized with the system mechanization and the run procedure. The pilot was informed as to the parameter being studied and the control mode in which he was operating before each series of runs. Each pilot was also asked to purposely put controller inputs into the system at the beginning of each run in order to get a feel of the system response. It was observed that the pilots were very reluctant to purposely use the treadles for yawing because they felt the treadles were incompatible with the two-axis controller.

Particular emphasis was placed upon the pilot evaluation of the control system response during the final stage of docking. The contact performance data were recorded primarily for use as an aid in establishing the range of final contact conditions incurred during the docking task. No attempt was made to utilize the performance data in determining satisfactory translational and attitude control characteristics.

In order for the pilots to satisfactorily rate the vehicle handling qualities, a nominal docking task was established. This standard maneuver started the pilot 175 feet behind the command module and at a radical displacement of 15 feet in different quadrants for each run. These values were reduced to 80 and 8 feet respectively for the astronauts due to the time involved for docking at the larger ranges. The pilot was given no initial attitudes or attitude rates and a nominal value of 2 feet for c.g. off-set

(ΔZ) was incorporated into the system for the entire study in order to make the configuration more realistic. This coupling effect also prevented the pilot from using only the translational control for docking.

PILOT PARTICIPATION

Three pilot-subjects were provided by NASA to participate in the program. One pilot-subject completed all the scheduled runs whereas the runs were divided between the other two. It is of significance that two of the subjects were Project Mercury Astronauts with actual space-flight experience. The background of each subject is presented below.

Name	R. Davidson-Pilot	J.H. Glenn-Astronaut	M.S. Carpenter-Astronaut
Organization	NASA - Manned Spacecraft Center	NASA - Manned Spacecraft Center	NASA - Manned Spacecraft Center
Total Flight Hours	3500	5400	3000
Total Jet Hours	250	2000	500
Helicopter Hours	0	0	15
Flight Test Hours	0	500	400
Flight Test Years	0	4	4
Simulator Time	200	Considerable	150
No. Production Runs	60	14	25

DISCUSSION OF RESULTS

General

Several exploratory runs were made prior to the production runs in order to check-out the system and to establish satisfactory nominal control system characteristics which were used during the thrust level evaluations. The nominal values selected from these exploratory runs are presented in Table II and were used until preliminary results were available.

Pilot opinion was employed in the major part of the study as the primary criterion for determining the acceptability or unacceptability of the control system characteristics investigated. However, performance parameters were recorded and analyzed for each run. The evaluation of visual aids and extreme initial conditions was based on these performance data rather than pilot opinion.

Thrust Level Study

Due to the significant effect of thrust level on the handling qualities and contact performance of the LEM, a satisfactory thrust level for each individual command mode was determined first. The pilot ratings with thrust variation for both translational control and attitude control are presented in Figures 15 through 18. Also shown is the relationship between acceleration and thrust (Figures 19 and 20). As was expected, the acceleration command (open-loop) for attitude control was definitely the most sensitive to thrust level and indicated that even a lower thrust than the minimum studied (6.25 lbs.) would perhaps be more desirable.

Although the translational control indicated a higher optimum thrust (30 lbs.), the thrust level of 6.25 lbs. was selected since the acceleration system was considered the back-up or emergency system. Moreover, the overall rating of the system revealed that the attitude control characteristics tended to be predominate in the open-loop system. The curves for the other two modes of attitude control have the same trend as the translational control but are more restricted in rating variation. A thrust level of 25 lbs. was selected for both the rate command attitude-hold modes and was used throughout the remainder of the study.

Attitude Control Study

This phase of the study consisted of a systematic variation of the maximum slewing rate and the attitude deadband for the rate command and rate command attitude-hold modes respectively. Only an exploratory study was made of the acceleration command mode with a minimum impulse provision. The parameters investigated during this phase of the study are presented in Table III.

Five values of maximum slewing rate were investigated in the rate command system with the same maximum rate placed in all three axes. These slewing rates were converted to stick sensitivities in the pitch, roll, and yaw axes and are presented in Figures 21 through 23. It should be noted that full pitch throw was approximately 50% greater than the roll stick throw which resulted in a greater stick sensitivity in the roll axis. These data indicated that the optimum stick sensitivities were 25, 28, and 23 deg/sec/inch for the pitch, roll, and yaw axes respectively. From preliminary results, stick sensitivities of 14.3°/sec/in for roll, 9.5°/sec/in for pitch,

and 10.0°/sec/in for yaw were selected. Although these selected stick sensitivities are lower than the optimum value shown by the ratings, there is only a half-point difference in the ratings.

Investigation of the rate command attitude-hold mode consisted of varying the attitude deadband from 1° to 8° in total width. The results are presented in Figure 24 and indicate the expected deterioration in pilot rating with increased deadband. It is noted, however, that the rate of deterioration is greater at the smaller deadbands and tends to level off at larger deadbands. The reason that the larger deadband had very little effect on pilot rating was due to the pilot correcting the attitude drift before the attitude-hold feature of the system made a correction. At the lower deadbands, however, a variation in the deadband was more noticeable since the attitude corrections made by the system were much quicker. A deadband of $\pm$ 2.0° was selected during this evaluation and used henceforth in the study.

The attitude controller was provided with a minimum impulse provision for the acceleration command mode. Since the minimum impulse provision was in the control system when two of the pilot-subjects arrived, this system was used to familiarize them with the simulation set-up. Pilot comments obtained for two different pulse durations (.0075 and .015 sec with 100 lbs. thrust) indicated that the disharmony between the translational and the attitude controller was unsatisfactory. For example, a normal pilot impulse on the translation control required from 4 to 8 pulses by the pilot on the attitude stick to correct the rotation induced by a nominal cross-coupling term (ΔZ = 2 ft.). This exploratory study of the impulse system

suggested the need for a dual pulse provision on the stick which would provide a single impulse at approximately 15% of stick and either a modulated pulse or a continuous pulse at 80-100% of full stick throw. Since time did not permit a revision of the impulse system, no conclusive results were obtained in relation to a satisfactory impulse duration.

Cross-Coupling Effects

Cross-coupling was investigated in two phases in order to determine the effect of the center-of-gravity movement and of the asymmetric thrust level on the handling qualities of the vehicle. Tables IV and V present the characteristics of the system and the parameters studied.

The effect of center-of-gravity variation on the handling qualities of the vehicle is reflected in the curves of Figures 25 through 27. The relation between the c.g. off-set (ΔZ) and the percent of attitude control necessary to balance the induced moment in each axis is presented in Figure 28. The shift of the center-of-gravity was most noticeable in the acceleration command mode. The rating deteriorates at the higher values of c.g. off-set because of the large inputs to attitude control necessary to counter balance the rotational motion. The pilot indicated that coupling was particularly bothersome during the delicate maneuvering stage (< 12 ft) of the docking task. However, no "unacceptable" conditions were indicated for the range of c.g. off-sets studied. This coupling effect was less bothersome in the rate command mode and diminished to an almost unnoticeable effect in the rate command attitude-hold mode. As a result, the ratings were all within the "satisfactory" region for these two command modes. It was observed

that the task of correcting the induced rotational moments seemed to become more routine with increased pilot learning.

The second phase of the cross-coupling study was concerned with asymmetric thrust levels on each pair of attitude thrusters. This configuration resulted in a translational motion induced by an attitude command. It should be noted that a nominal c.g. off-set of 2 feet was also present and produced an additional cross-coupling effect as described in the previous paragraph. As a result, the coupling term affected the pilot ratings of the asymmetric thrust variation (Figures 29 through 31). The presence of the c.g. off-set caused the curves to shift to higher ratings than would have been obtained without this nominal off-set. Although a corresponding existence of c.g. coupling effect would be the most real-life condition, it may be somewhat misleading here. For instance, a thrust difference of 5% shows a pilot rating of approximately 3.75 for the acceleration command mode. This rating would more accurately be 2.75 if not for the ΔZ of 2 feet; consequently, the curve would shift downward by a rating point. Likewise, the curves for the rate command and rate command attitude-hold modes would shift downward by .5 rating point. A rapid deterioration in pilot rating beyond 5% is shown for the acceleration and rate command modes and was probably due to the fact that the pilot was encountering a two-fold correction requirement. Upon entering a translation input to correct the translational motion, the pilot induced an additional rotational motion which was adverse and necessitated correcting. The pilot then found himself in a closed-loop error correction process until the motion was reduced to a small magnitude. The effect of

asymmetric thrust was less pronounced in the attitude-hold mode since the rotation induced by a translational command was kept within the deadband limit by the autopilot.

Visual Aids and Initial Conditions

Up to this phase of the study, the pilot was provided with a TV image, an all-attitude indicator (AAI), and a timer. However, a matching set of stripes was added to the docking ports of the LEM and the command-module upon request of the astronauts. It was felt that these stripes increased depth perception at very close ranges. The pilot was then required to fly various runs without the benefit of the AAI and subsequent runs with a gun-sight type visual aid (pair of cross-bars). The effect of the addition or deletion of certain visual aids on pilot performance is presented in Figures 32 through 35. The attitude positions are presented as performance indicies since the AAI and gun-sight aid were used almost exclusively for attitude positioning.

Since only a few runs were made (one pilot-subject) without the AAI and subsequent runs with the gun-sight aid, it was felt that the performance data were insufficient to provide a significant statistical average. For example, only 3 data samples were averaged for runs with no aids and for runs with just the gun-sight-aid; whereas 85 data samples were averaged for runs with the AAI. However, with the exception of the gun-sight aid, the trend of the standard deviation increases with the deletion of visual aids. The pilots commented during the study that it was very difficult to detect

attitude positions accurately (especially pitch and yaw) without the aid of the all-attitude indicator. There is no significant performance correlation with pilot comments for the yaw attitude which indicates that the pilot did not attempt to correct the yaw. In fact, the pilots tended to avoid the use of the treadles throughout the study since it was felt that they were totally inadequate for satisfactory yaw control.

The performance data obtained for 3 different initial conditions (Table VI) were not sufficient to make a statistical comparison. However, it was noticed from the data that the three different conditions had little or no significant effect on pilot performance.

Performance

Although the major part of the study was based on pilot opinion exclusively, performance data were recorded for each run. The primary performance data recorded consisted of translational displacements and rates, angular displacements and rates, and fuel consumption.

A summary of performance data for the translational characteristics are presented in Figure 36 and indicate a reasonably good correlation between the performance and pilot opinion. However, no consistent trend exists for the attitude characteristics shown in Figures 37 and 38. The data indicates that the pilot detected translational displacements and rates easier than he detected angular displacements and rates. As a result, the contact conditions for translation were more representative of possible contact limits than the attitude conditions. No correlation was obtainable for fuel consumption since the pilots were asked to maneuver the vehicle at the beginning of the mission.

CONCLUSIONS

1. If the acceleration command mode is to function as the back-up system, a low level of thrust will be necessary for an on-off configuration.

2. Higher thrust levels are satisfactory for the rate command and rate command attitude-hold modes. Thrusts up to 100 lbs. were within the acceptable range for both translational and attitude control (with satisfactory control system characteristics).

3. The maximum slewing rates studied (for full stick throw) did not cause significant deterioration in the pilots' evaluation of the handling qualities and were within the "satisfactory" region.

4. Although attitude deadbands between 0 and 2° caused a rapid deterioration in pilot opinion, the rating changed only from 1.25 to 2.5.

5. Center-of-gravity off-set presented no real problem in the rate command and rate command attitude-hold modes (PR < 3.5 for c.g. off-sets up to 4 ft). However, it was felt that the difficulty in the acceleration command mode (unsatisfactory for c.g. off-set of 2 ft) could be eliminated somewhat with additional pilot learning.

6. Asymmetric thrust with c.g. off-set produced a more difficult situation. Beyond 5% asymmetric thrust the pilot opinion deteriorated rapidly from an "acceptable" to an "unacceptable" condition for the rate command and acceleration command modes.

7. The all-attitude indicator was definitely beneficial to the pilot.

8. Optimum pilot control was attained with the rate command attitude-hold system (for satisfactory control system characteristics).

RECOMMENDATIONS

1. Before arriving at any conclusions concerning the control system characteristics, a similar investigation should be conducted with more satisfactory controllers. It was felt that foot treadles were totally inadequate for proper yaw control - a three-axis-attitude controller would be more satisfactory.

2. Tolerable limits on the final conditions should be established and incorporated into the study for the docking task.

3. A more detailed study of an impulse system in the acceleration command mode for high thrust levels (e.g. 100 lb) should be made.

4. Explore the possibility of a dual thrust system, since a very low thrust level is desirable at close ranges while a larger thrust is tolerable at longer ranges.

PILOT OPINION RATING SYSTEM FOR UNIVERSAL USE

	ADJECTIVE RATING	NUMERICAL RATING	DESCRIPTION	PRIMARY MISSION ACCOMPLISHED?	CAN BE DOCKED
NORMAL OPERATION	SATISFACTORY	1	EXCELLENT, INCLUDES OPTIMUM	YES	YES
		2	GOOD, PLEASANT TO FLY	YES	YES
		3	SATISFACTORY, BUT WITH SOME MILDLY UNPLEASANT CHARACTERISTICS	YES	YES
EMERGENCY OPERATION	UNSATISFACTORY	4	ACCEPTABLE, BUT WITH UNPLEASANT CHARACTERISTICS	YES	YES
		5	UNACCEPTABLE FOR NORMAL OPERATION	DOUBTFUL	YES
		6	ACCEPTABLE FOR EMERGENCY CONDITION ONLY*	DOUBTFUL	YES
NO OPERATION	UNACCEPTABLE	7	UNACCEPTABLE EVEN FOR EMERGENCY CONDITION*	NO	DOUBTFUL
		8	UNACCEPTABLE - DANGEROUS	NO	NO
		9	UNACCEPTABLE - UNCONTROLLABLE	NO	NO
	CATASTROPHIC	10	MOTIONS POSSIBLY VIOLENT ENOUGH TO PREVENT PILOT ESCAPE		

* (FAILURE OF A STABILITY AUGMENTER)

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THRUST LEVEL STUDIES

COMMAND MODE	*THRUST (LBS)	ϵ_{ON} (DEG)	ϵ_{ON}-ϵ_{OFF} (PITCH & YAW)	ϵ_{ON} - ϵ_{OFF} (ROLL)	K (DEG/SEC)	a_0	a_1 (SEC)
ACCELERATION	6.25	-	-	-	-	1.0	1.0
	12.5	-	-	-	-	1.0	1.0
	25	-	-	-	-	1.0	1.0
	50	-	-	-	-	1.0	1.0
	100	-	-	-	-	1.0	1.0
RATE	6.25	±2.0	.5	.5	15.0	1.0	4.0
	12.5	±2.0	.5	.5	15.0	1.0	4.0
	25	±2.0	.5	.5	15.0	1.0	4.0
	50	±2.0	.5	.5	15.0	1.0	4.0
	100	±2.0	.5	.5	15.0	1.0	4.0
RATE WITH ATTITUDE-HOLD	6.25	±2.0	.048	.128	15.0	1.0	2.0
	12.5	±2.0	.098	.256	15.0	1.0	2.0
	25	±2.0	.195	.500	15.0	1.0	2.0
	50	±2.0	.390	1.020	15.0	1.0	2.0
	100	±2.0	.780	2.040	15.0	1.0	2.0

* Denotes Parameters Varied

Table II

ATTITUDE CONTROL STUDIES

COMMAND MODE	THRUST (LBS)	ϵ_{ON} (DEG)	ϵ_{ON}-ϵ_{OFF} (PITCH & YAW) DEG	ϵ_{ON}-ϵ_{OFF} (ROLL) DEG	K DEG/SEC	α_0	α_1 (SEC)
RATE	25	±2.0	.50	.50	* 5.0	1.0	4.0
	25	±2.0	.50	.50	10.0	1.0	4.0
	25	±2.0	.50	.50	20.0	1.0	4.0
	25	±2.0	.50	.50	40.0	1.0	4.0
RATE WITH ATTITUDE-HOLD	25	*± .5	.195	.50	15.0	1.0	2.0
	25	±1.0	.195	.50	15.0	1.0	2.0
	25	±2.0	.195	.50	15.0	1.0	2.0
	25	±4.0	.195	.50	15.0	1.0	2.0

Table III

NORTH AMERICAN AVIATION, INC.
COLUMBUS DIVISION
COLUMBUS 16, OHIO

CROSS COUPLING EFFECTS

(CG OFF-SET)

COMMAND MODE	THRUST (LBS)	ϵ_{ON} (DEG)	ϵ_{ON}-ϵ_{OFF} (PITCH & YAW) DEG	ϵ_{ON}-ϵ_{OFF} (ROLL) DEG	K DEG/ SEC	a_1 SEC	*ΔZ FT
ACCELERATION	6.25	-	-	-	-	1.0	1
	6.25	-	-	-	-	1.0	2
	6.25	-	-	-	-	1.0	4
RATE	25.0	± 2.0	.50	.50	15	4.0	1
	25.0	± 2.0	.50	.50	15	4.0	2
	25.0	± 2.0	.50	.50	15	4.0	4
RATE WITH ATTITUDE-HOLD	25.0	± 2.0	.195	.50	15	2.0	1
	25.0	± 2.0	.195	.50	15	2.0	2
	25.0	± 2.0	.195	.50	15	2.0	4

NOTE: a_o = 1 for entire study

NORTH AMERICAN AVIATION, INC.
COLUMBUS DIVISION
COLUMBUS 16, OHIO

CROSS-COUPLING EFFECTS

(Thrust Differential)

COMMAND MODE	THRUST (LBS)	SYSTEM CHARAC-TERISTICS	ΔZ FT	$*\Delta T_\theta$ %T	$*\Delta T_\phi$ %T	$*\Delta T_\psi$ % T
ACCELERATION	6.25 6.25 6.25	SAME AS FOR TABLE IV	2.0 2.0 2.0	2.5 5.0 10.0	2.5 5.0 10.0	2.5 5.0 10.0
RATE	25.0 25.0 25.0	SAME AS FOR TABLE IV	2.0 2.0 2.0	2.5 5.0 10.0	2.5 5.0 10.0	2.5 5.0 10.0
RATE WITH ATTITUDE-HOLD	25.0 25.0 25.0	SAME AS FOR TABLE IV	2.0 2.0 2.0	2.5 5.0 10.0	2.5 5.0 10.0	2.5 5.0 10.0

Table V

NORTH AMERICAN AVIATION, INC.
COLUMBUS DIVISION
COLUMBUS 16, OHIO

VISUAL AIDS AND INITIAL CONDITIONS

(Initial Conditions Variations)

COMMAND MODE	THRUST (LBS)	SYSTEM CHARAC-TERISTICS	$*X_o$ FT	$*Y_o$ FT	$*Z_o$ FT	$*\dot{X}_o$ FT/ SEC	$*\dot{Y}_o$ FT/ SEC	$*\dot{Z}_o$ FT/ SEC
ACCELERATION	6.25 6.25 6.25	SAME AS FOR TABLE IV	175 75 75	11 11 25	10.4 10.4 12.0	3 1.0 1.0	.8 1.0 1.0	.5 0 0
RATE	25.0 25.0 25.0	SAME AS FOR TABLE IV	175 75 75	11 11 25	10.4 10.4 12.0	3 1.0 1.0	.8 1.0 1.0	.5 0 0
RATE WITH ATTITUDE-HOLD	25.0 25.0 25.0	SAME AS FOR TABLE IV	175 75 75	11 11 25	10.4 10.4 12.0	3 1.0 1.0	.8 1.0 1.0	.5 0 0

Table VI

NORTH AMERICAN AVIATION, INC.
COLUMBUS DIVISION
COLUMBUS 16, OHIO

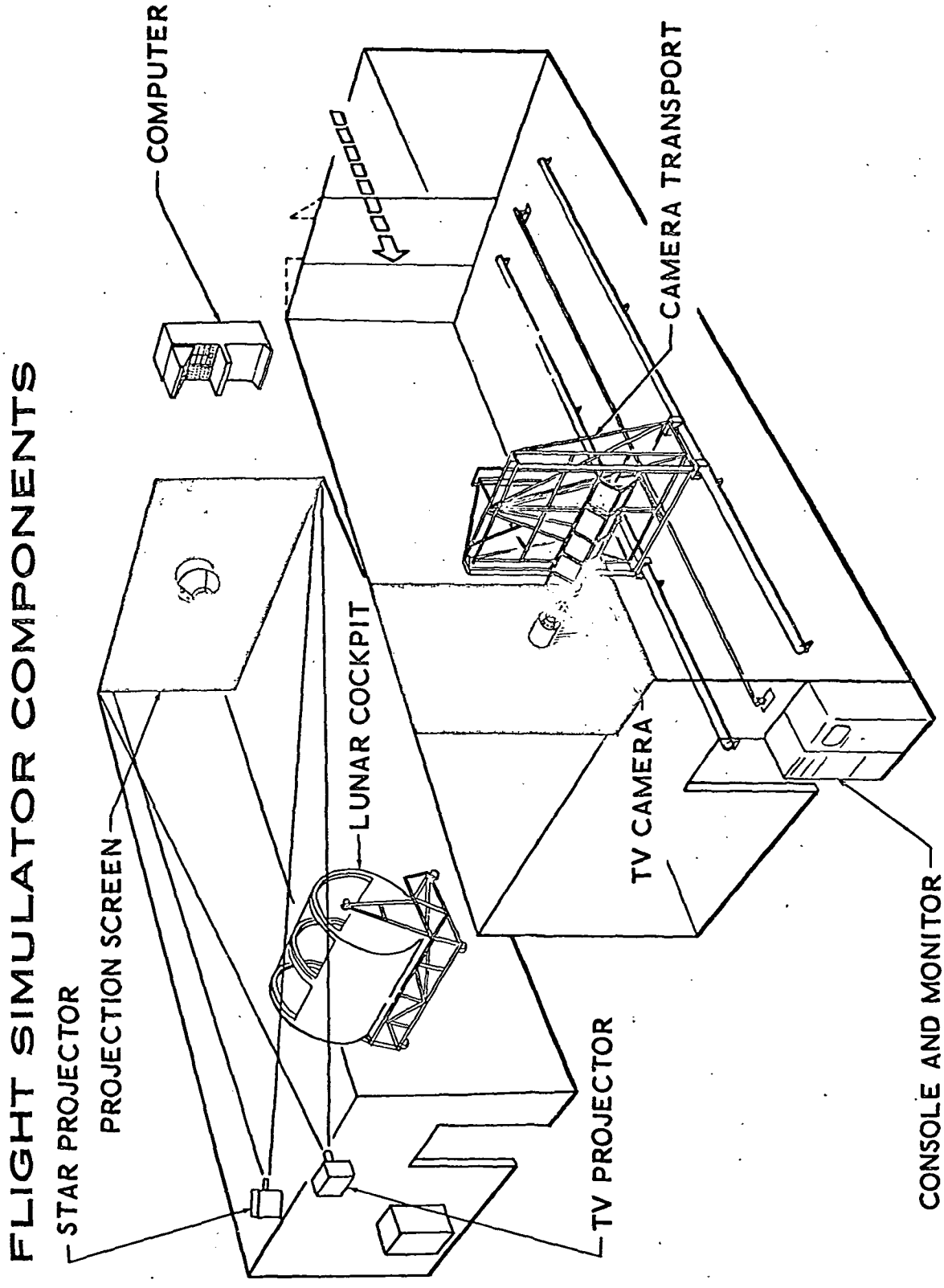

FLIGHT SIMULATOR COMPONENTS
COMPUTER
CAMERA TRANSPORT
STAR PROJECTOR
PROJECTION SCREEN
LUNAR COCKPIT
TV CAMERA
TV PROJECTOR
CONSOLE AND MONITOR

Figure 1

LUNAR COCKPIT

FIGURE 2

COCKPIT INSTRUMENTATION

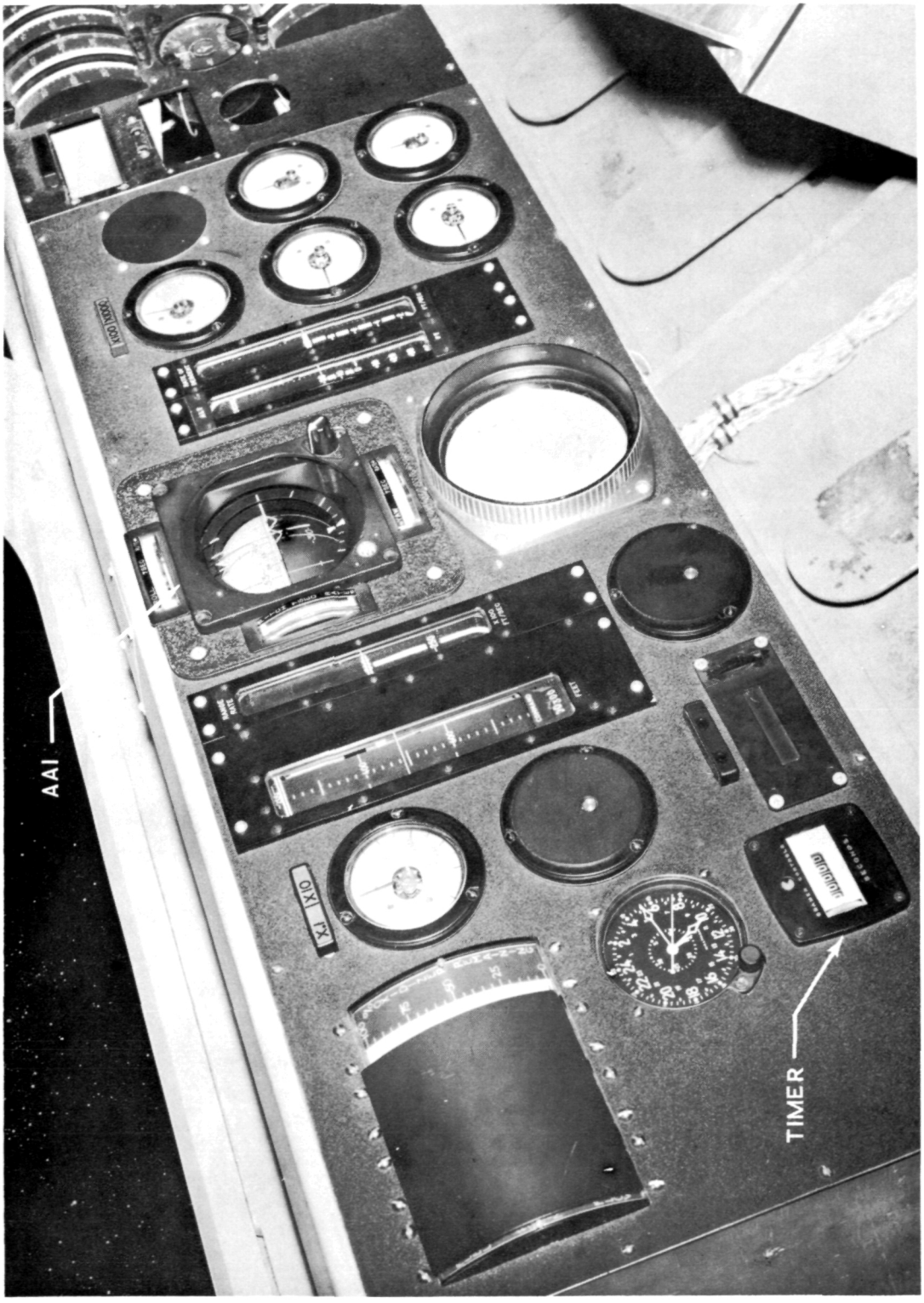


FIGURE 3

CONTROLLERS

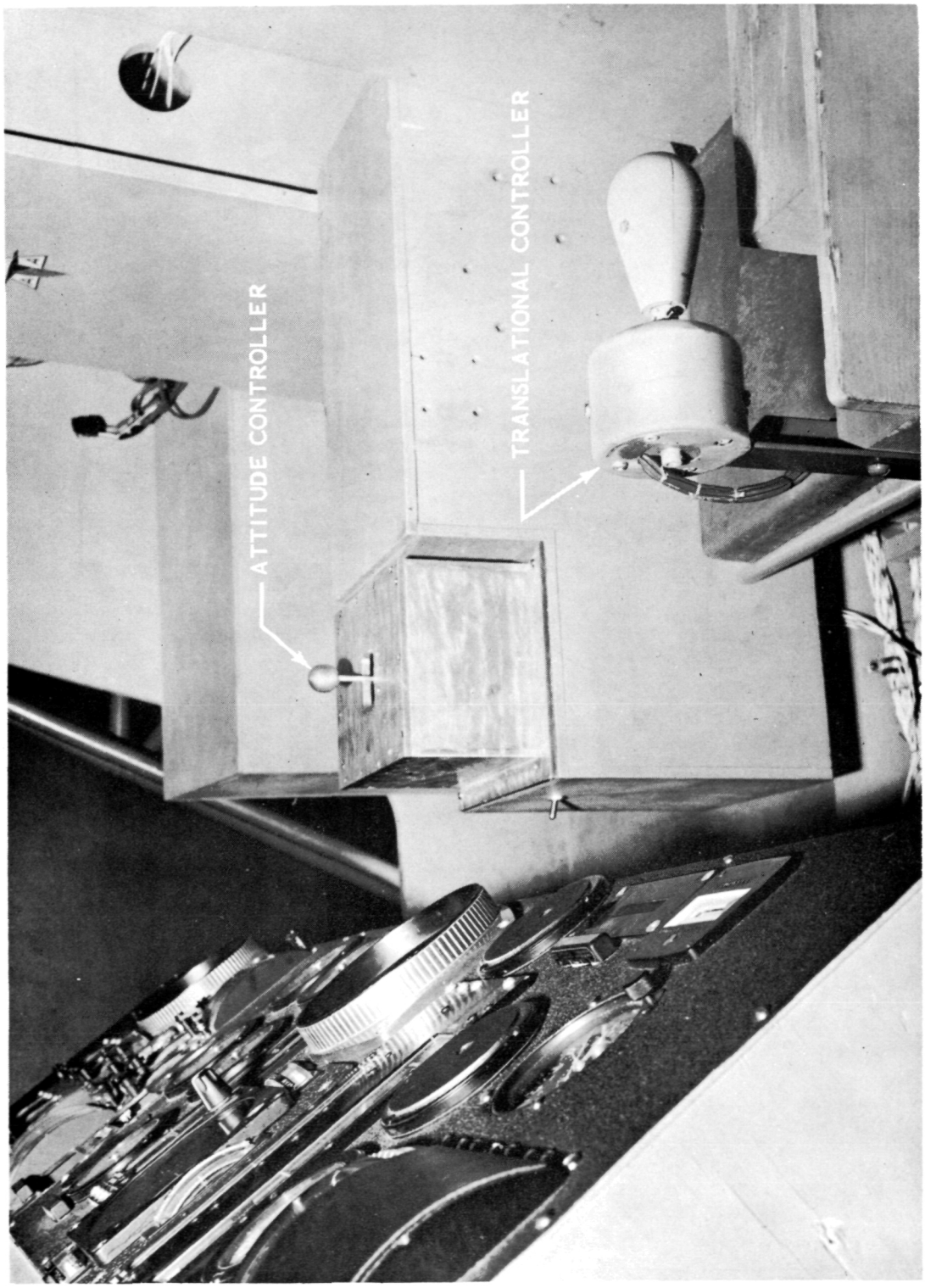


FIGURE 4

ANALOG COMPUTER FACILITY

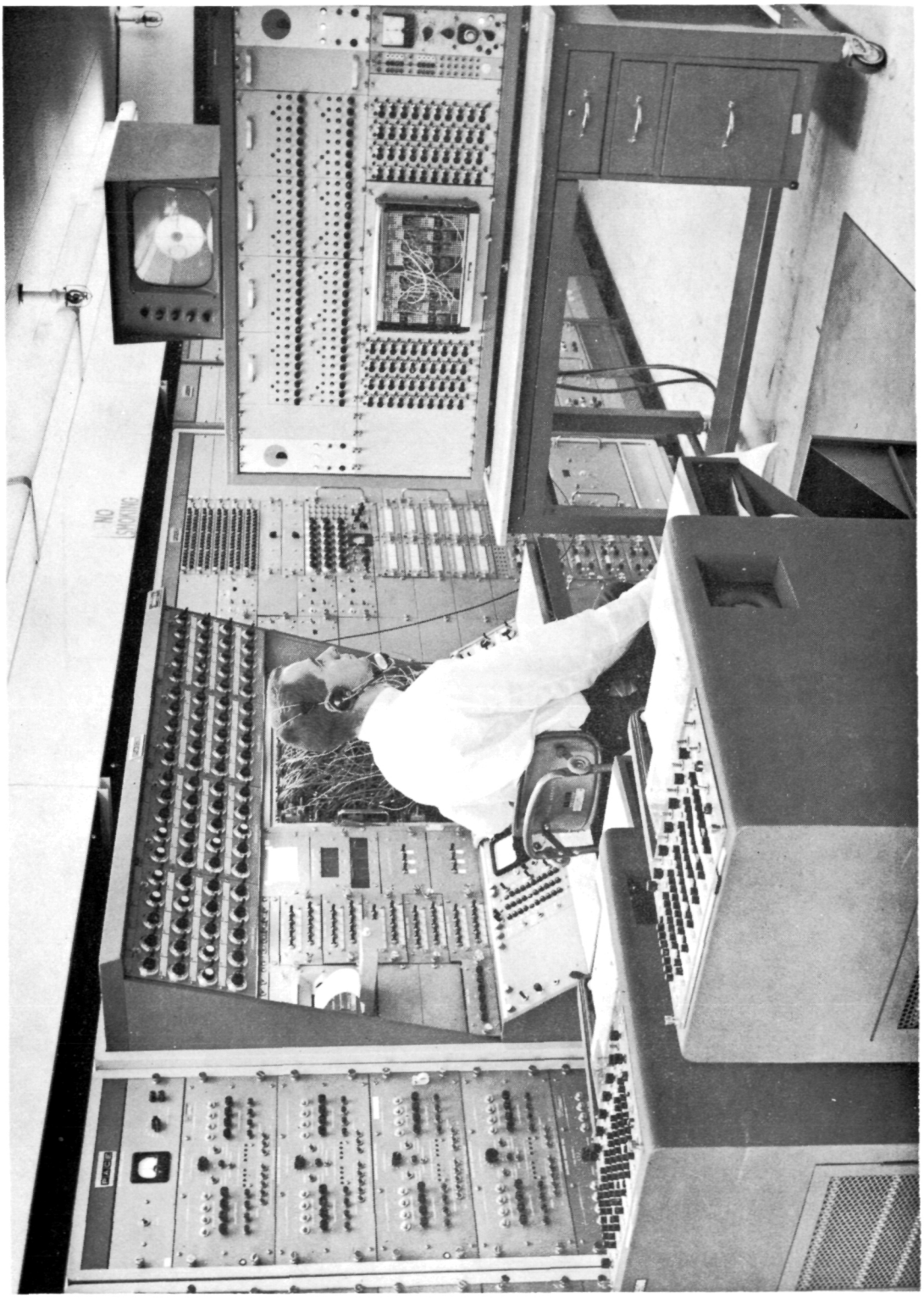


FIGURE 5

TV CAMERA RIG AND APOLLO COMMAND MODULE

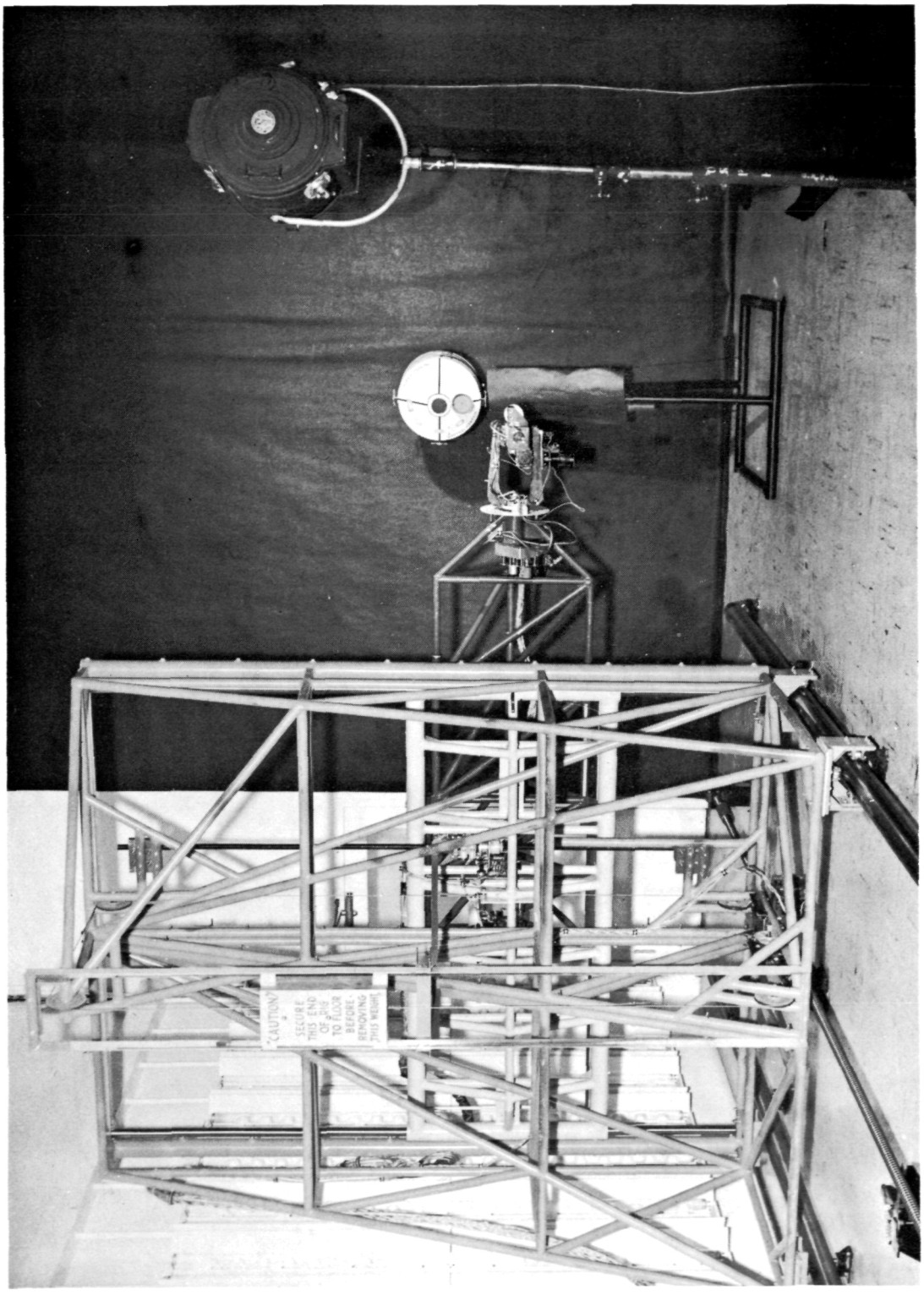
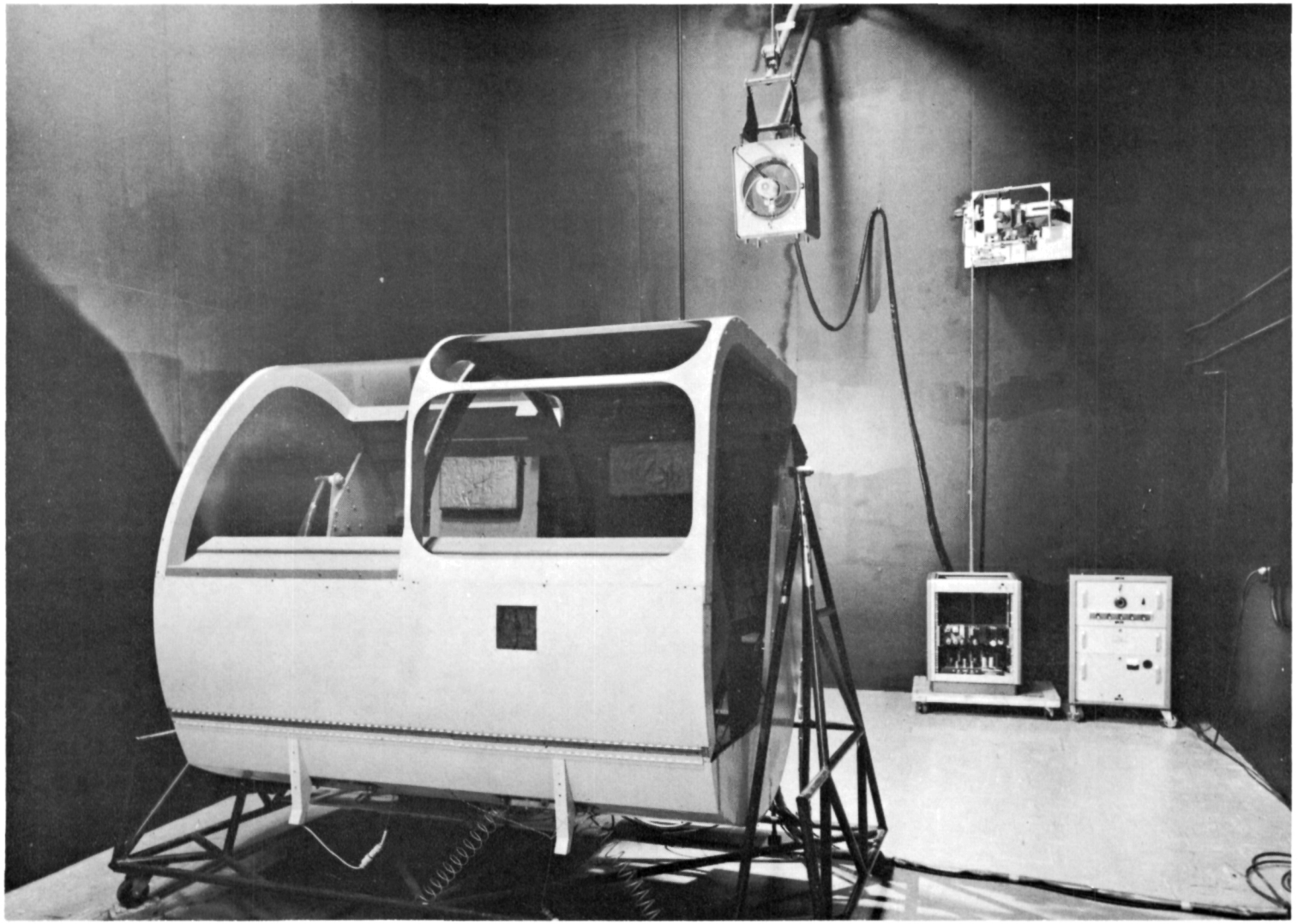


FIGURE 6

VISUAL PRESENTATION SIMULATOR ROOM

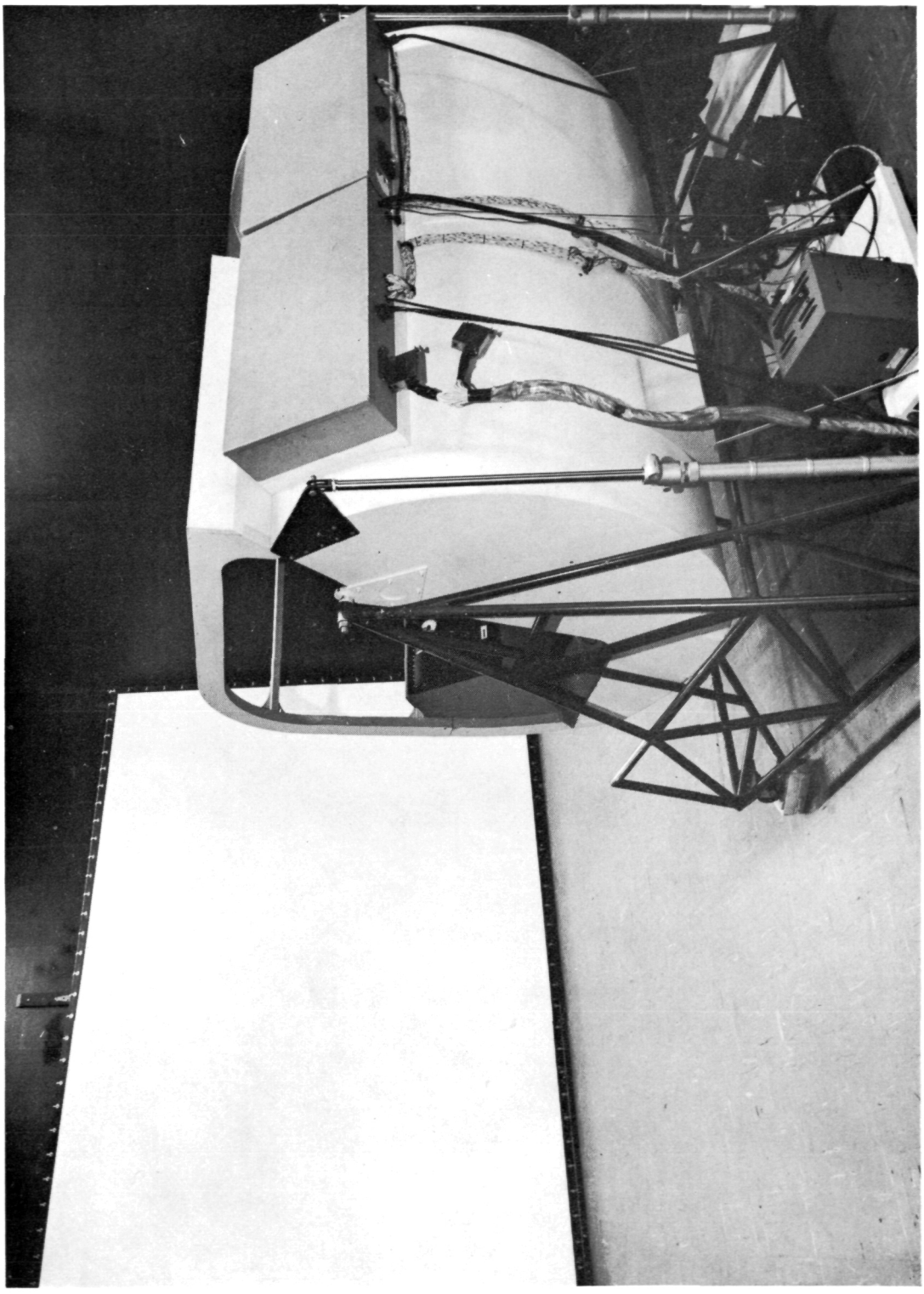


COCKPIT, TV-PROJECTOR AND STAR PROJECTOR

NORTH AMERICAN AVIATION, INC.
COLUMBUS DIVISION
COLUMBUS 16, OHIO

FIGURE 7

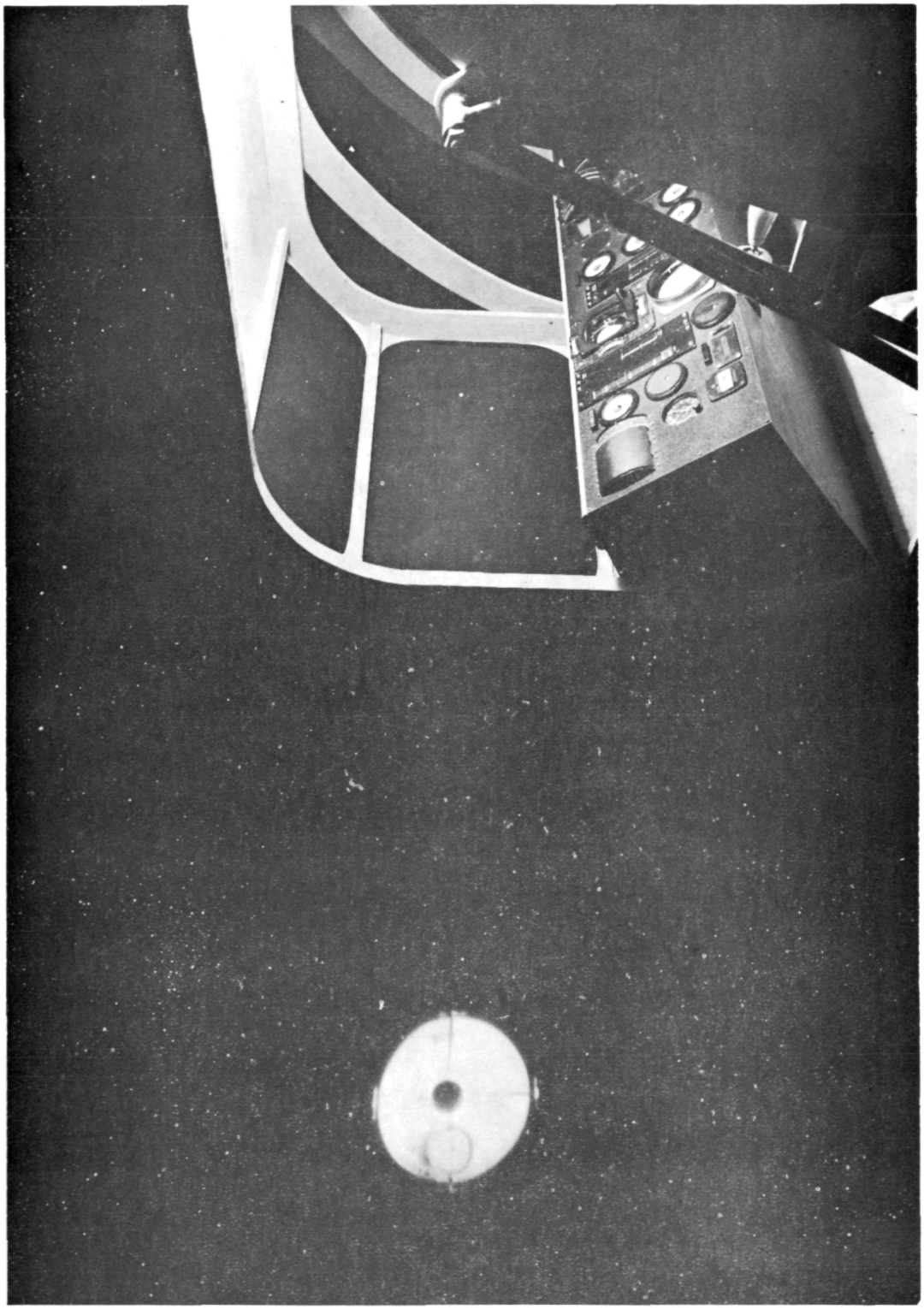
VISUAL PRESENTATION SIMULATOR ROOM



COCKPIT AND TV-SCREEN

FIGURE 8

VISUAL PRESENTATION SIMULATOR ROOM



COCKPIT AND TV-SCREEN

FIGURE 9

SIMULATOR FLOW DIAGRAM

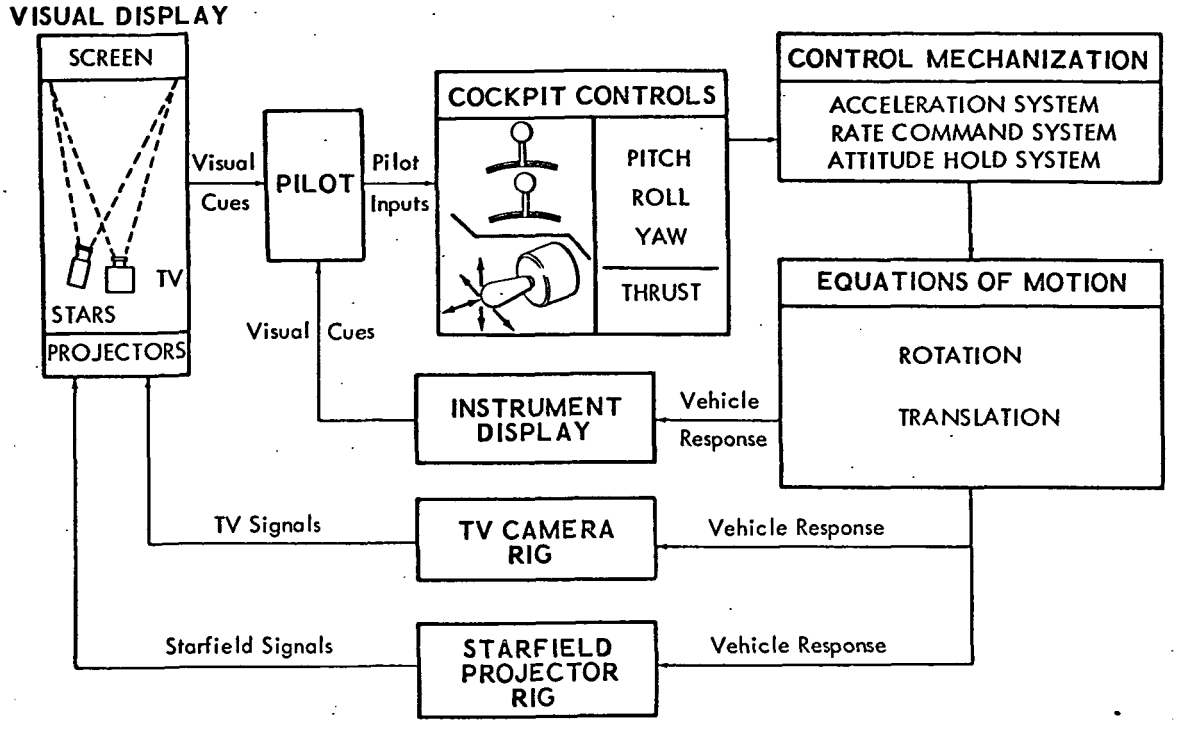


Figure 10

ATTITUDE CONTROL SYSTEM

RATE COMMAND

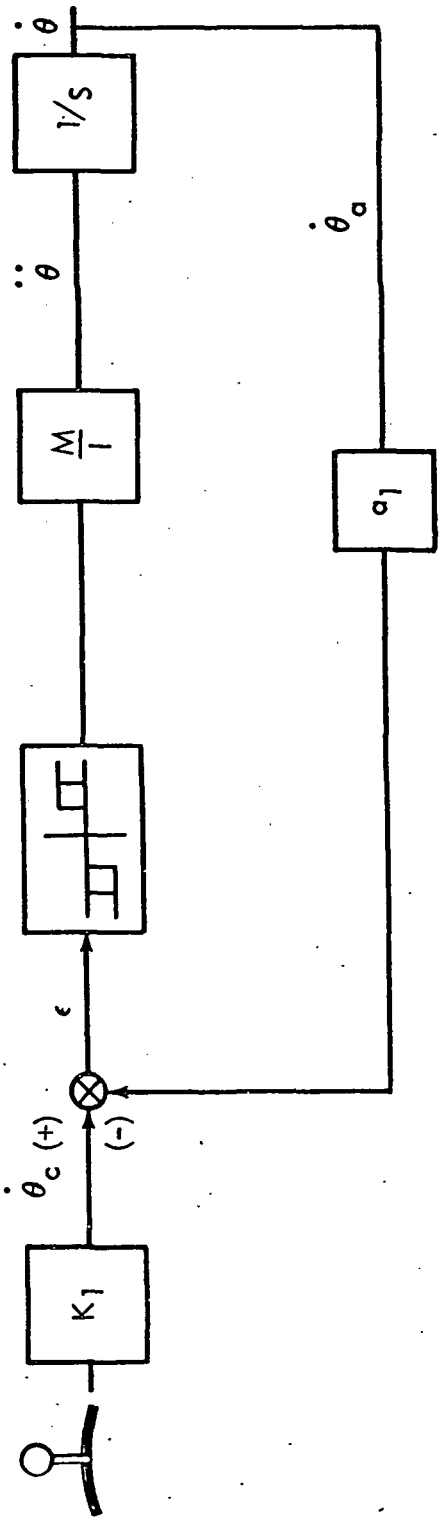
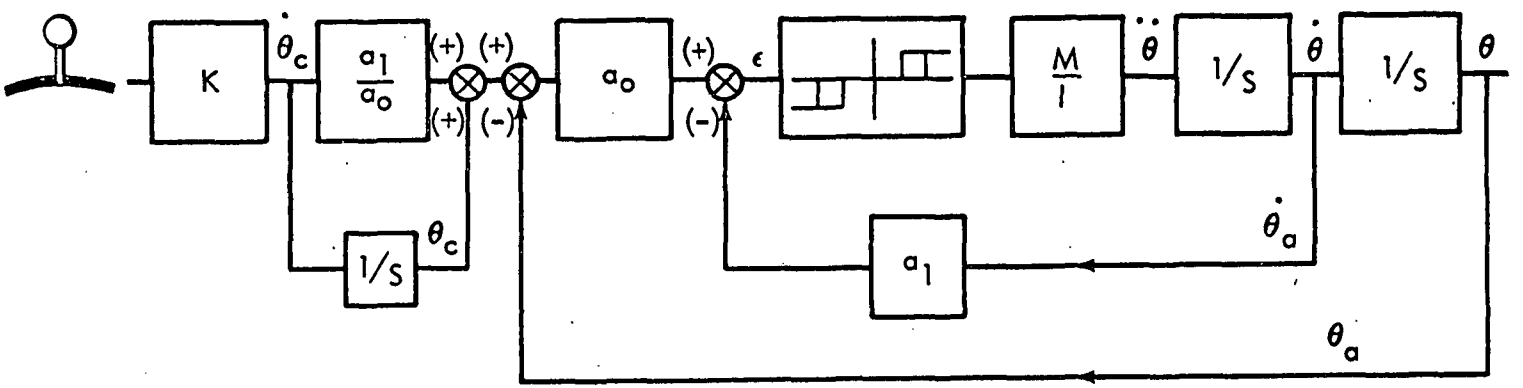


Figure 11

ATTITUDE CONTROL SYSTEM

RATE COMMAND WITH ATTITUDE-HOLD



ERROR SIGNAL $\epsilon = a_0 (\theta_c - \theta_a) + a_1 (\dot{\theta}_c - \dot{\theta}_a)$

Figure 12

NORTH AMERICAN AVIATION, INC.
COLUMBUS DIVISION
COLUMBUS 16, OHIO

ATTITUDE CONTROL SYSTEM

ACCELERATION COMMAND (OPEN-LOOP)

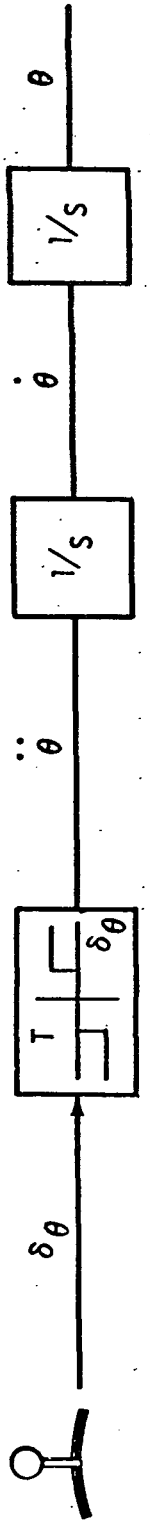


Figure 13

ATTITUDE CONTROL SYSTEM

ACCELERATION COMMAND WITH MINIMUM IMPULSE

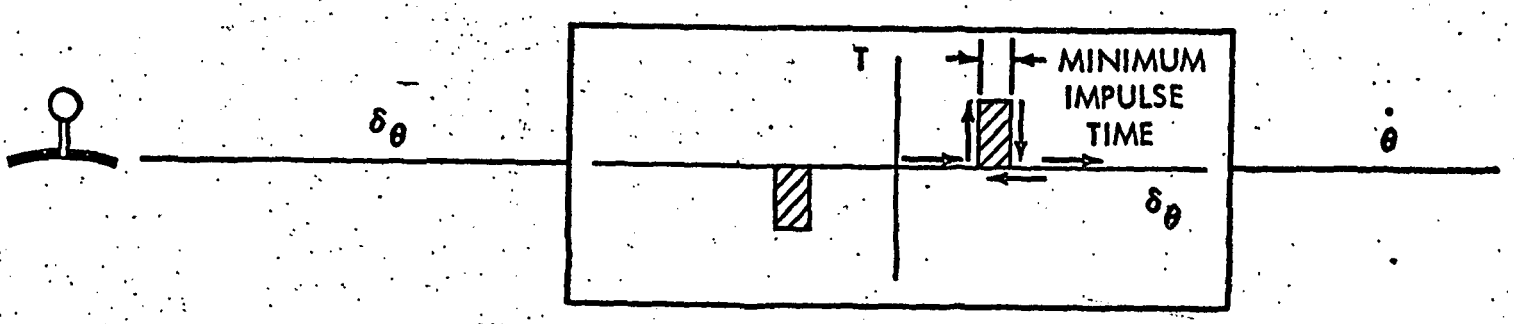


Figure 14

IMPULSE OBTAINED AT 15% FULL THROW OF STICK

NORTH AMERICAN AVIATION, INC.
COLUMBUS DIVISION
COLUMBUS 16, OHIO

THRUST VARIATION

TRANSLATIONAL CONTROL

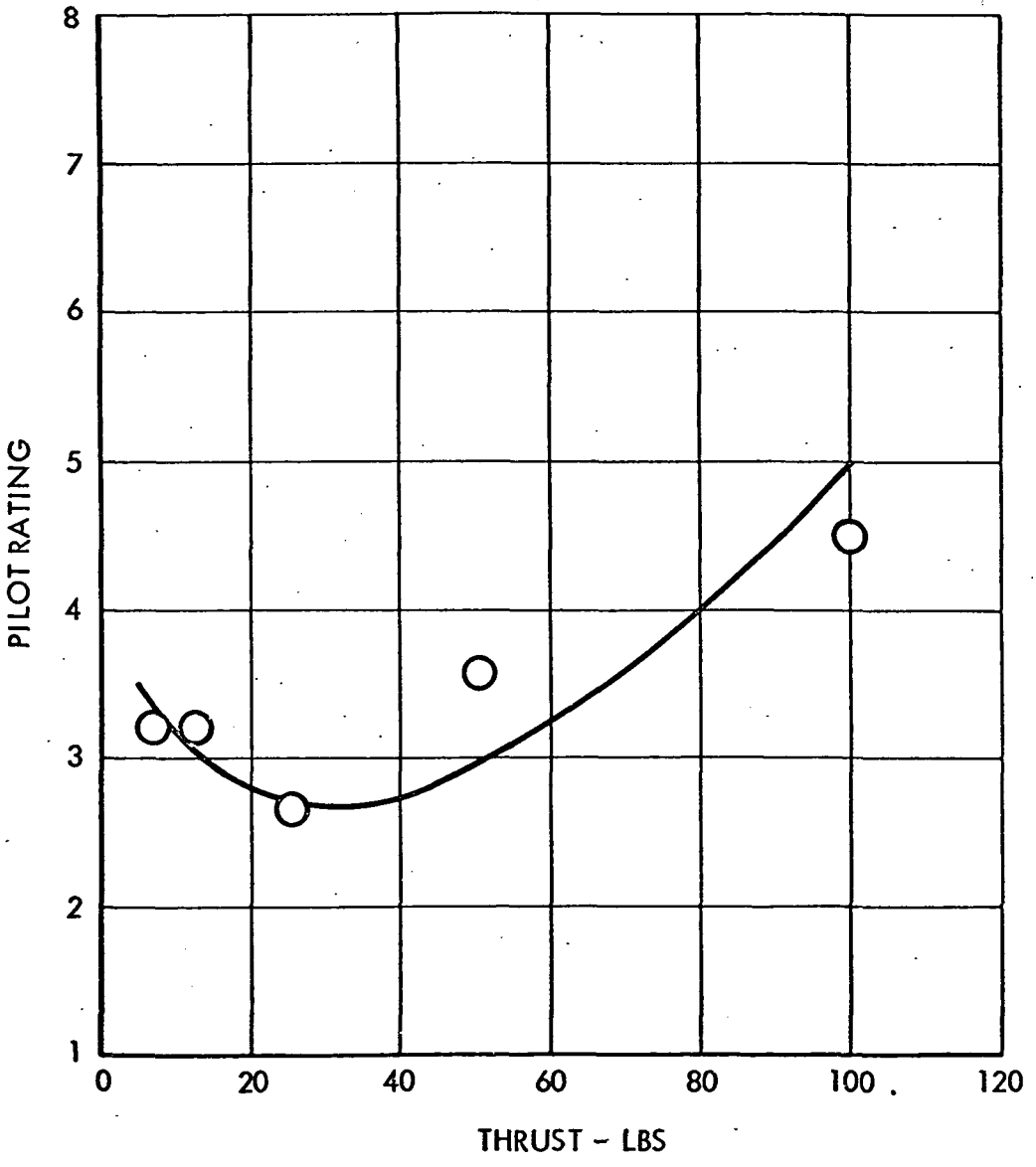


Figure 15

THRUST VARIATION

ATTITUDE CONTROL

ACCERERATION COMMAND

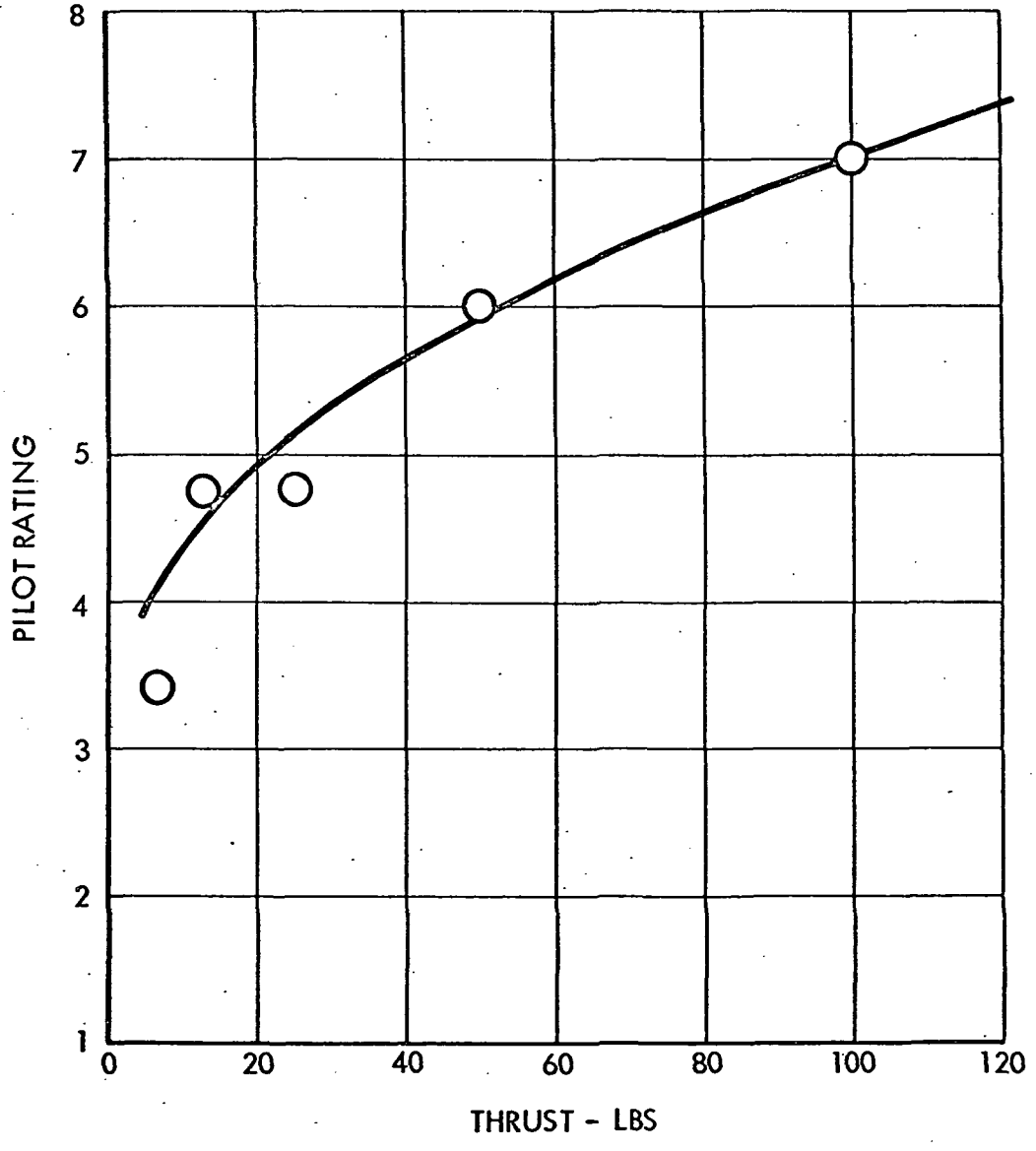


Figure 16

THRUST VARIATION
ATTITUDE CONTROL

RATE COMMAND

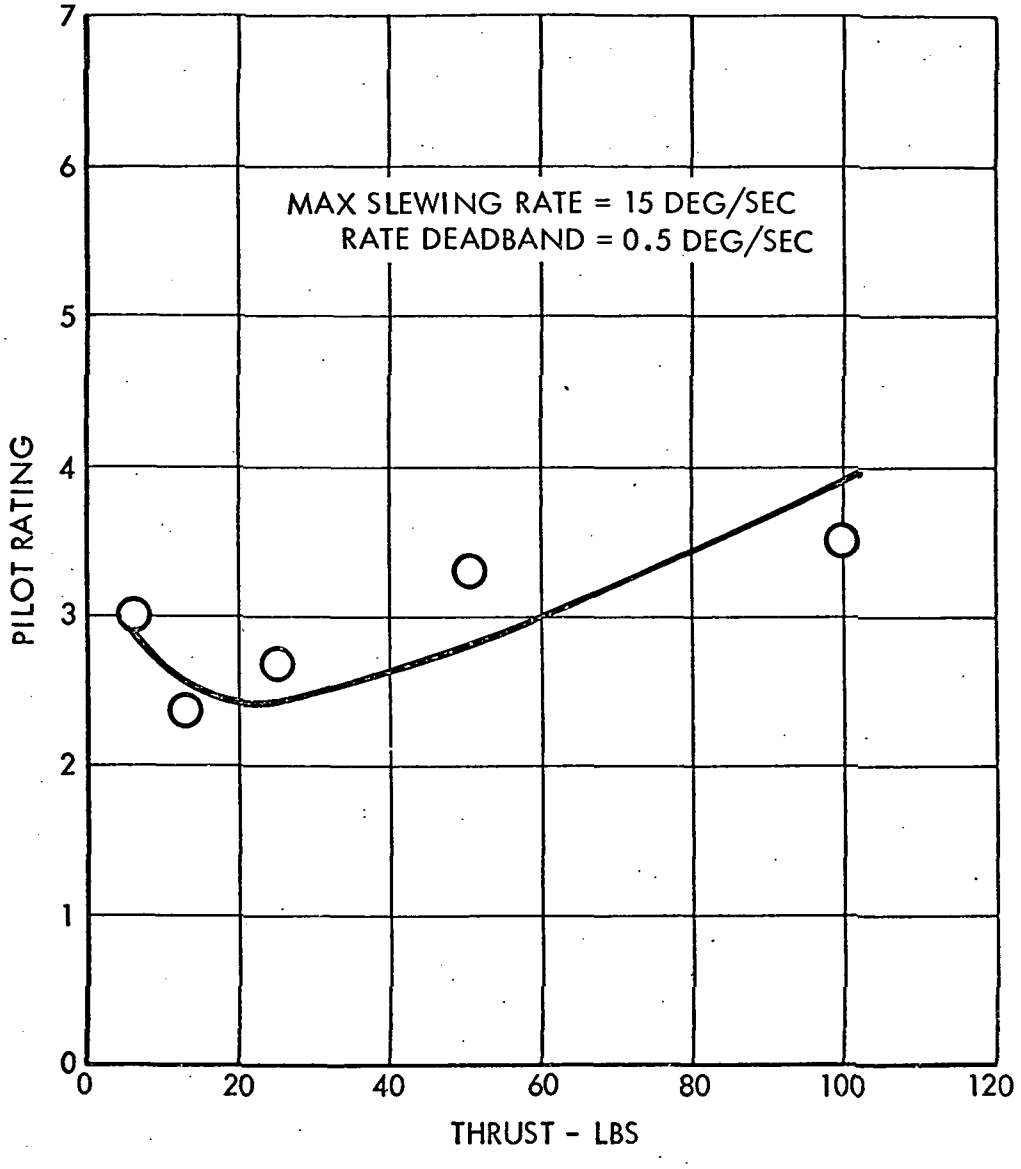


Figure 17

THRUST VARIATION

ATTITUDE CONTROL

RATE COMMAND ATTITUDE-HOLD

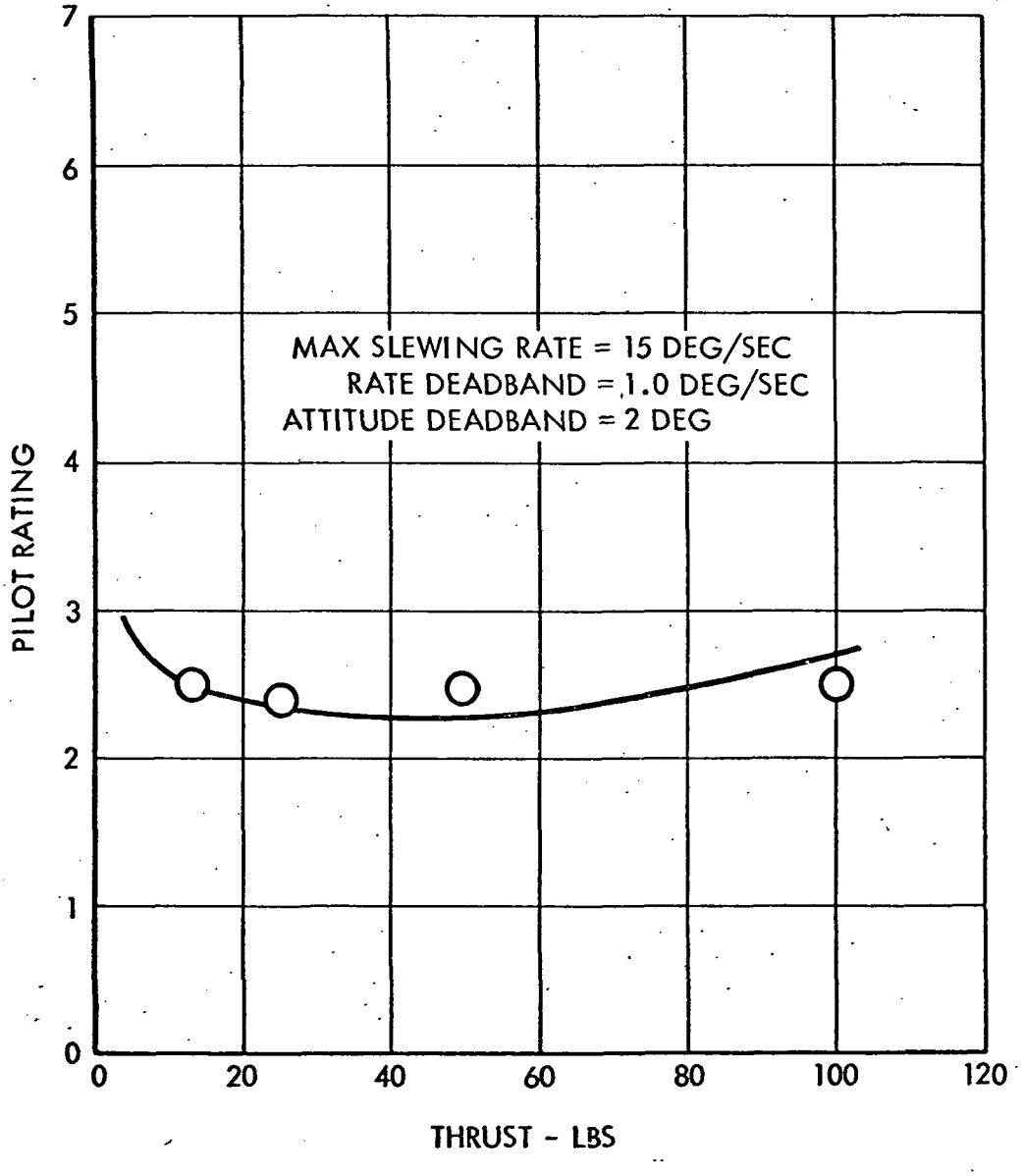


Figure 18

THRUST VARIATION

TRANSLATIONAL CONTROL

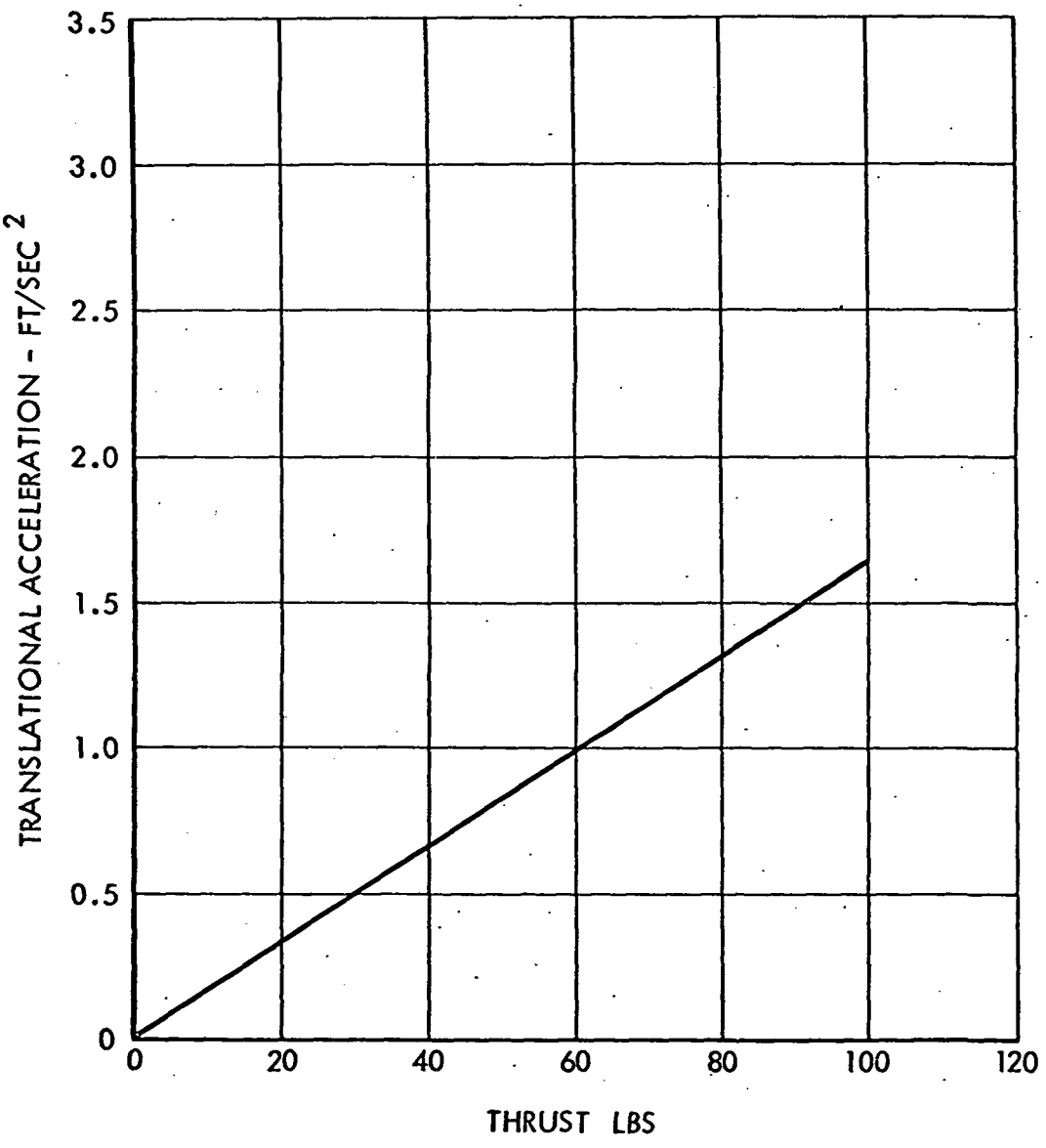


Figure 19

THRUST VARIATION

ATTITUDE CONTROL

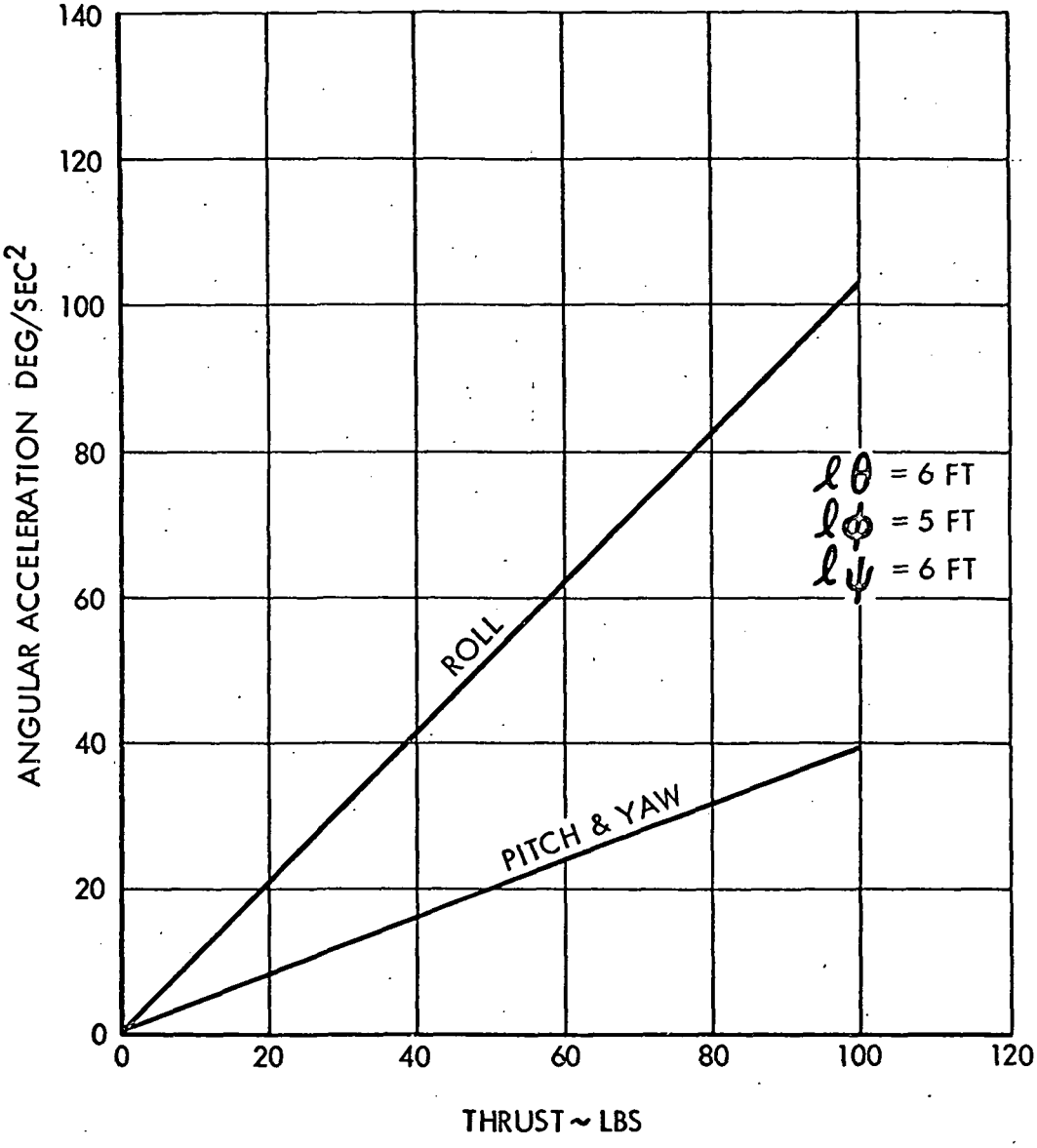


Figure 20

MAXIMUM SLEWING RATE VARIATION

ATTITUDE CONTROL

RATE COMMAND

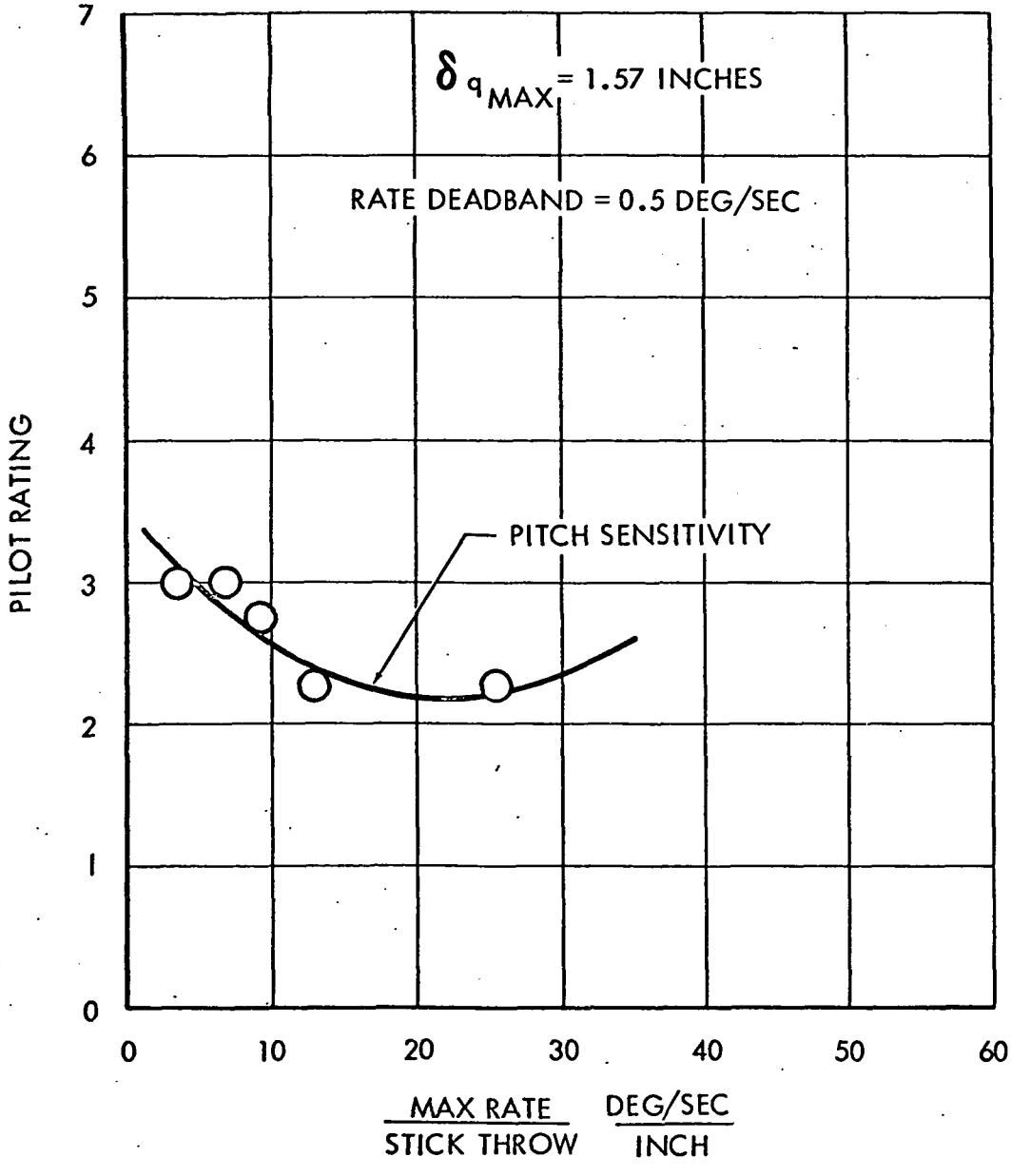


Figure 21

MAXIMUM SLEWING RATE VARIATION

ATTITUDE CONTROL

RATE COMMAND

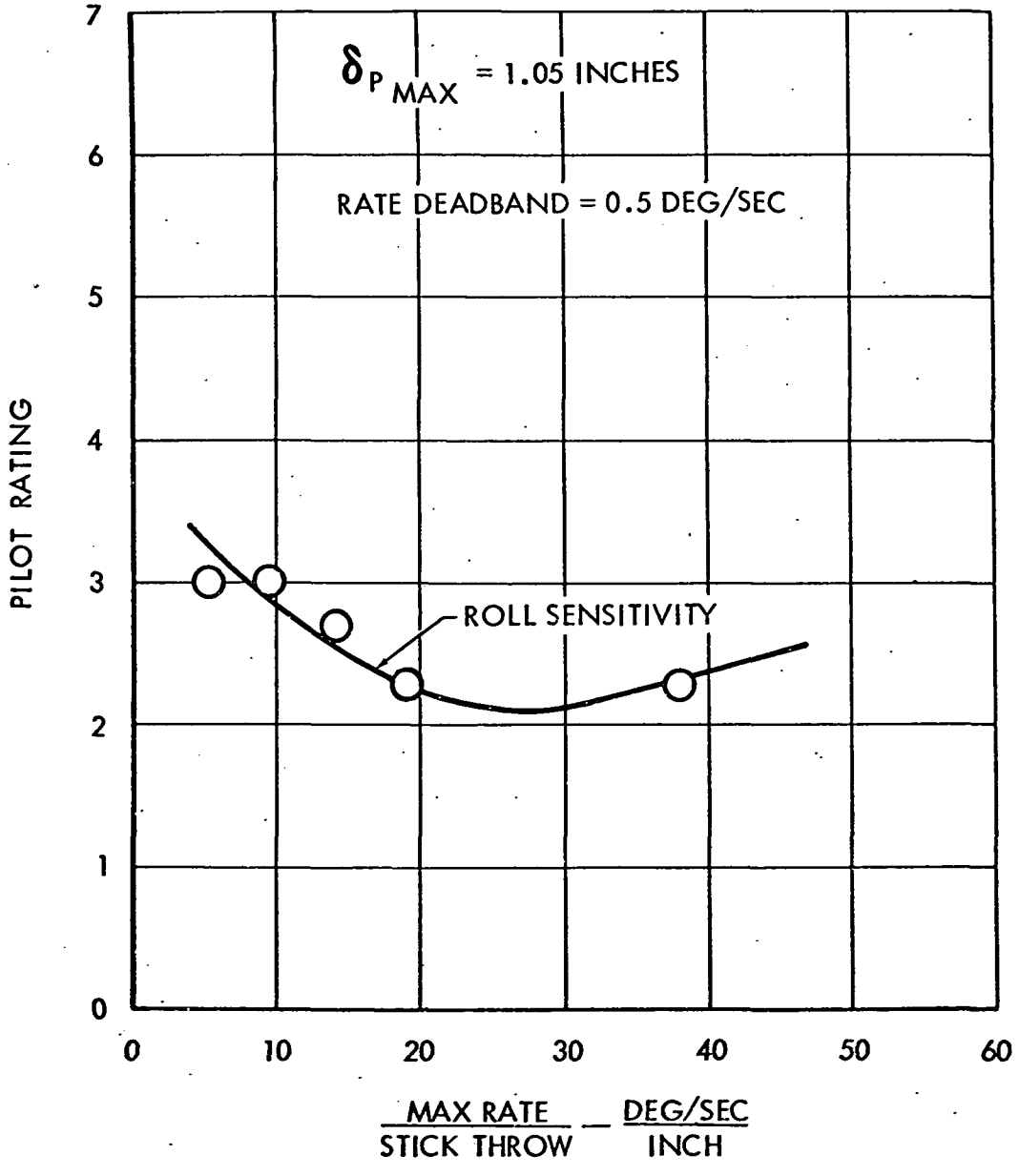


Figure 22

MAXIMUM SLEWING RATE VARIATION

ATTITUDE CONTROL

RATE COMMAND

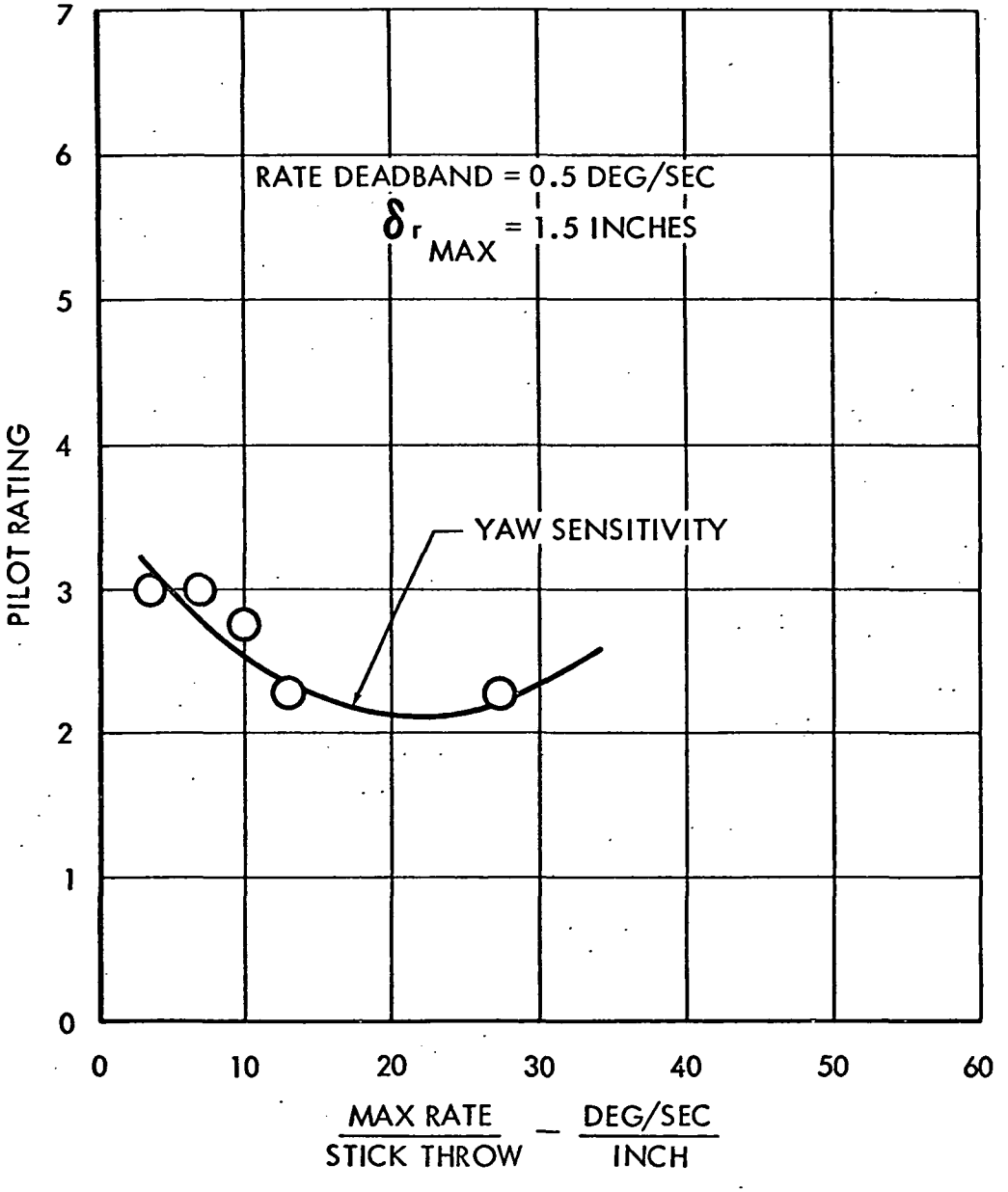


Figure 23

DEAD BAND VARIATION

ATTITUDE CONTROL

RATE COMMAND ATTITUDE-HOLD

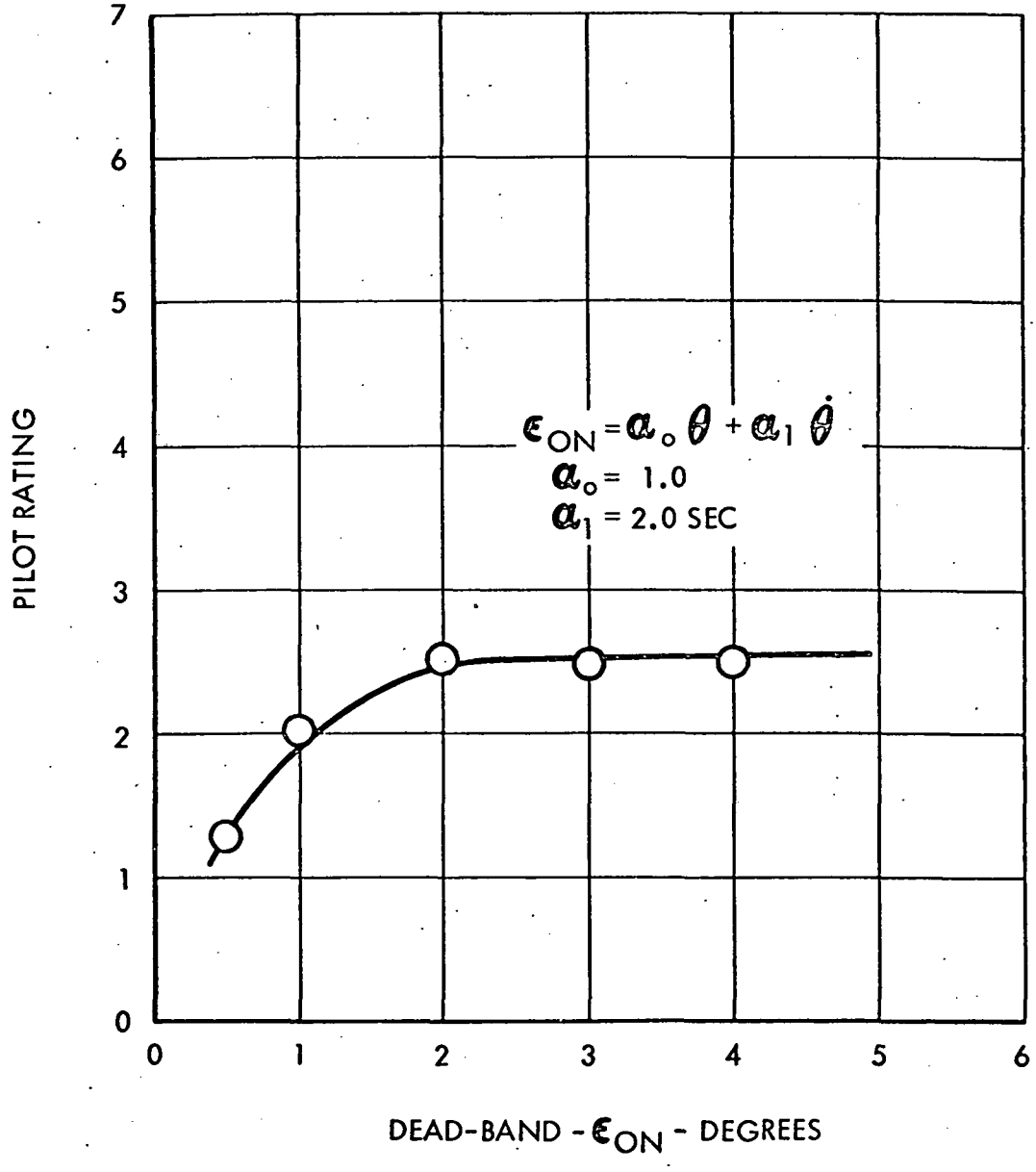


Figure 24

CROSS-COUPLING EFFECTS

CG OFF-SET

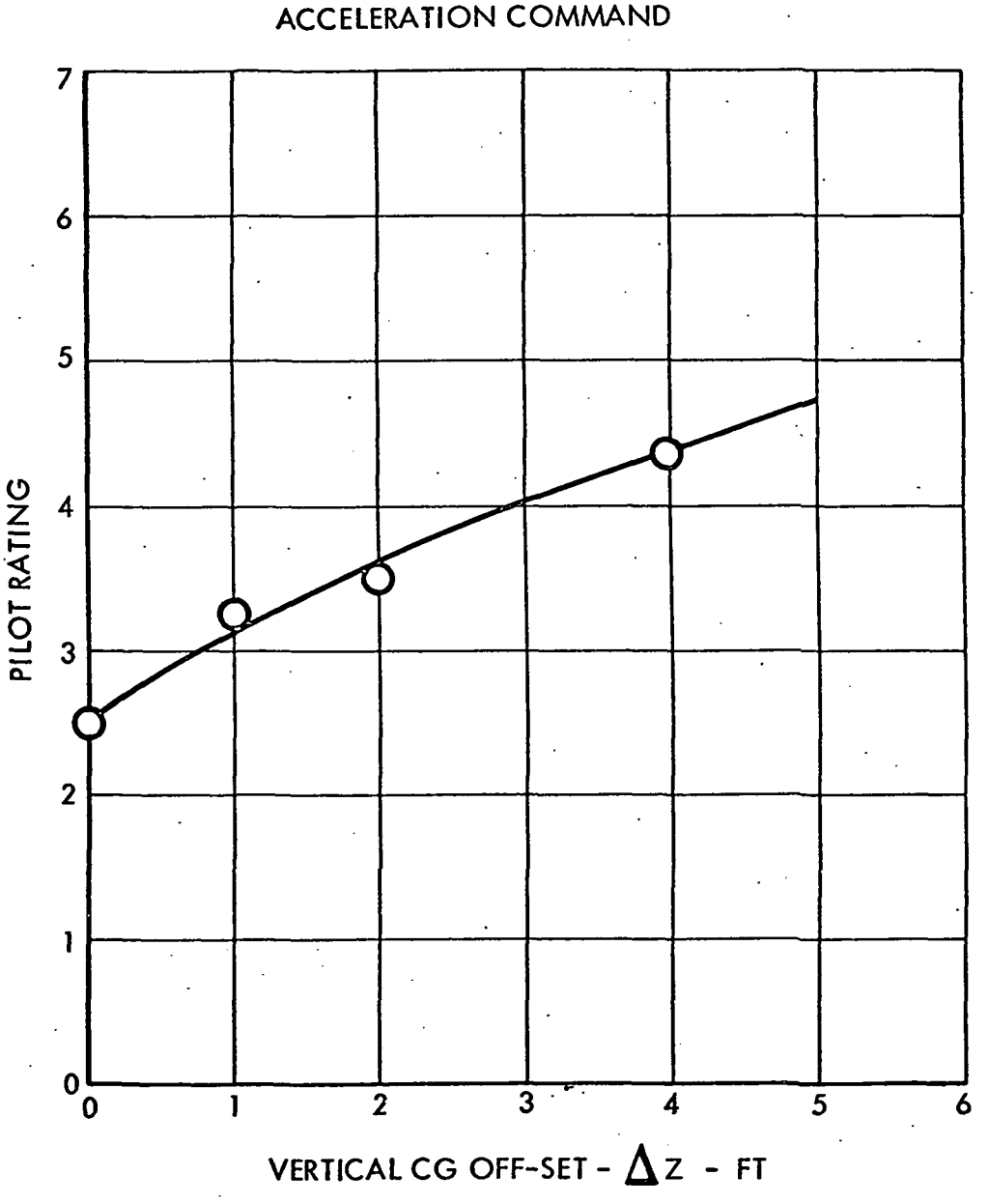


Figure 25

CROSS - COUPLING EFFECTS

CG OFF-SET

RATE COMMAND

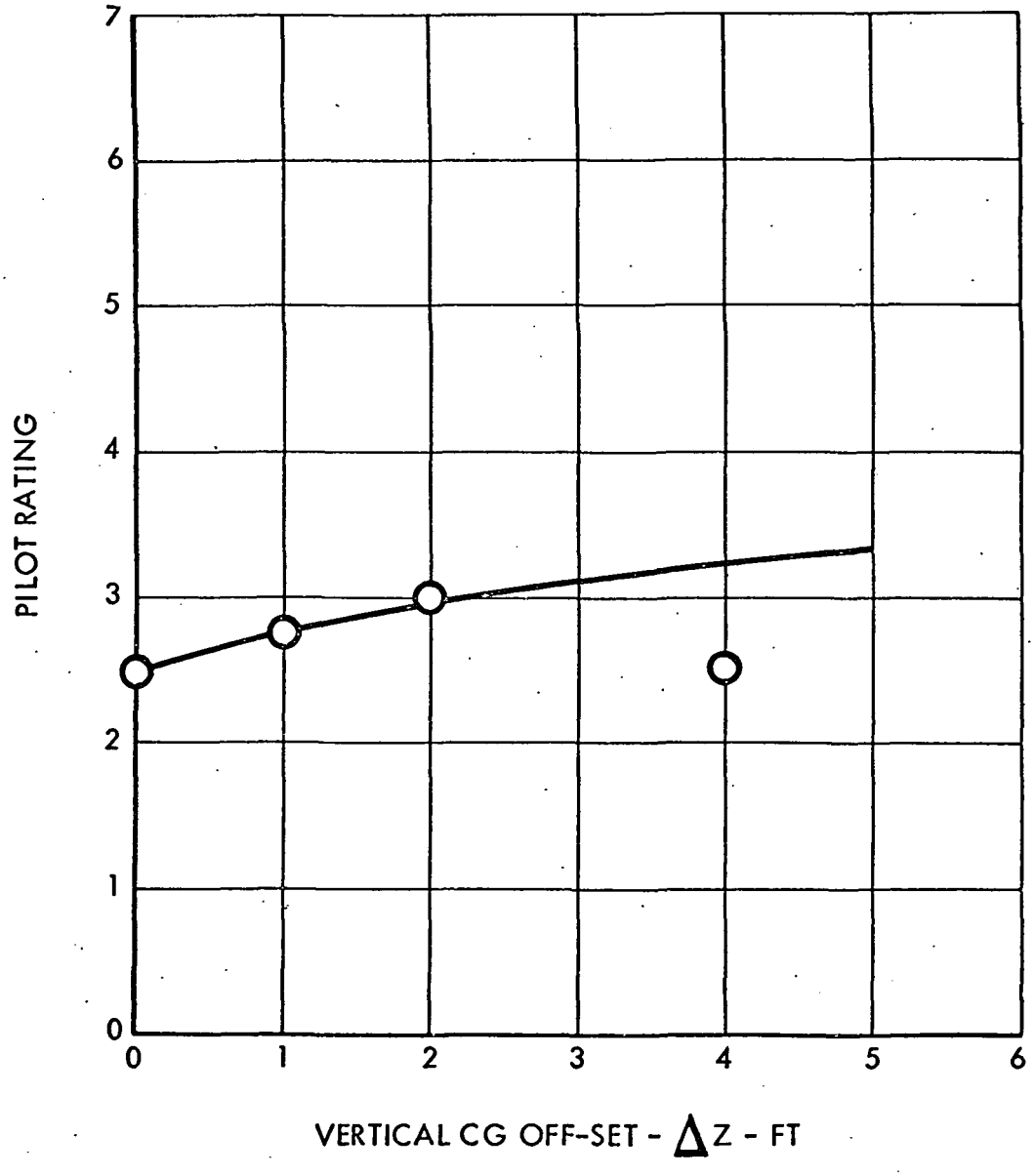


Figure 26

CROSS COUPLING EFFECTS

CG OFF-SET

RATE COMMAND ATTITUDE-HOLD

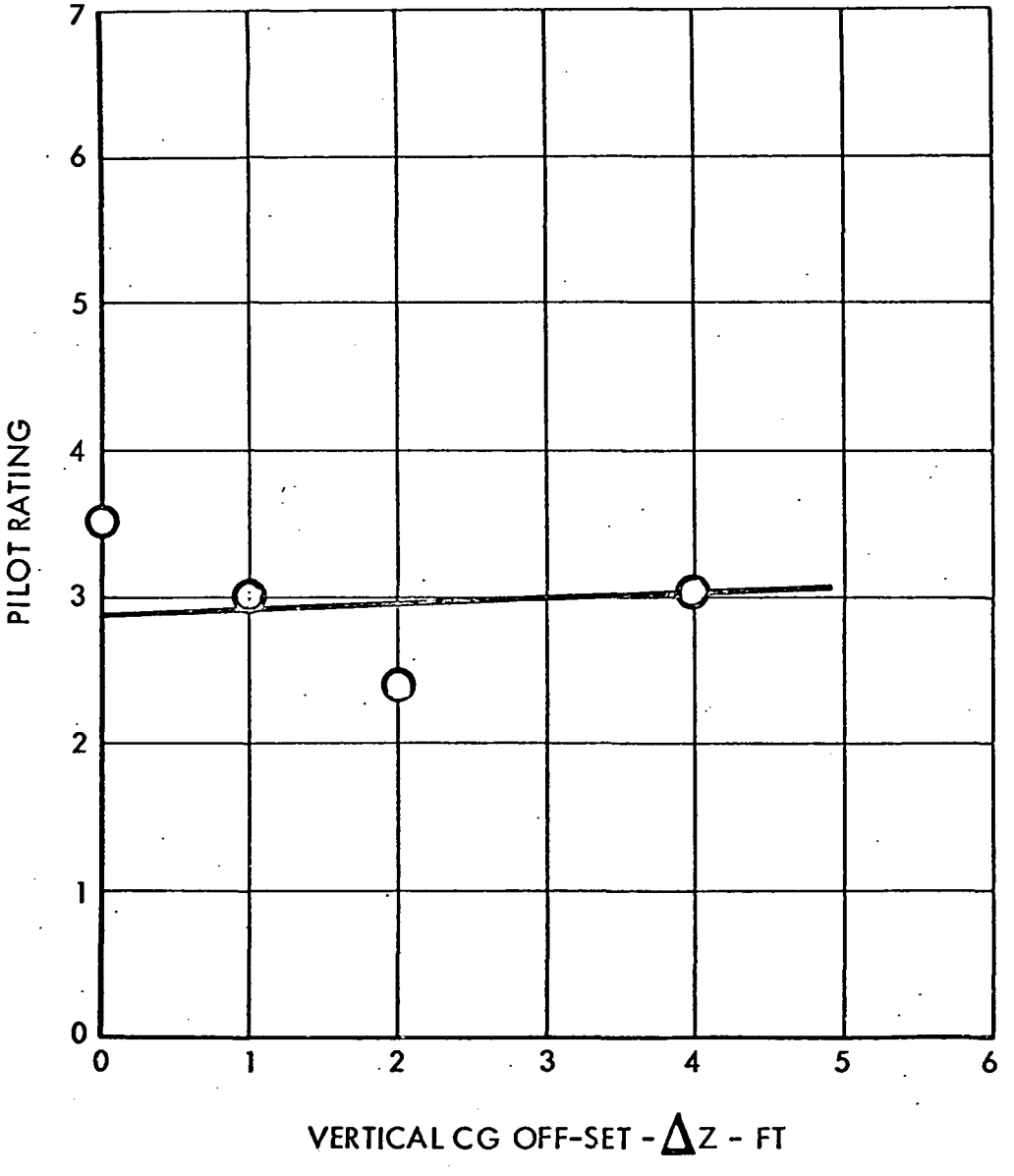


Figure 27

CROSS COUPLING EFFECTS

CG OFF-SET

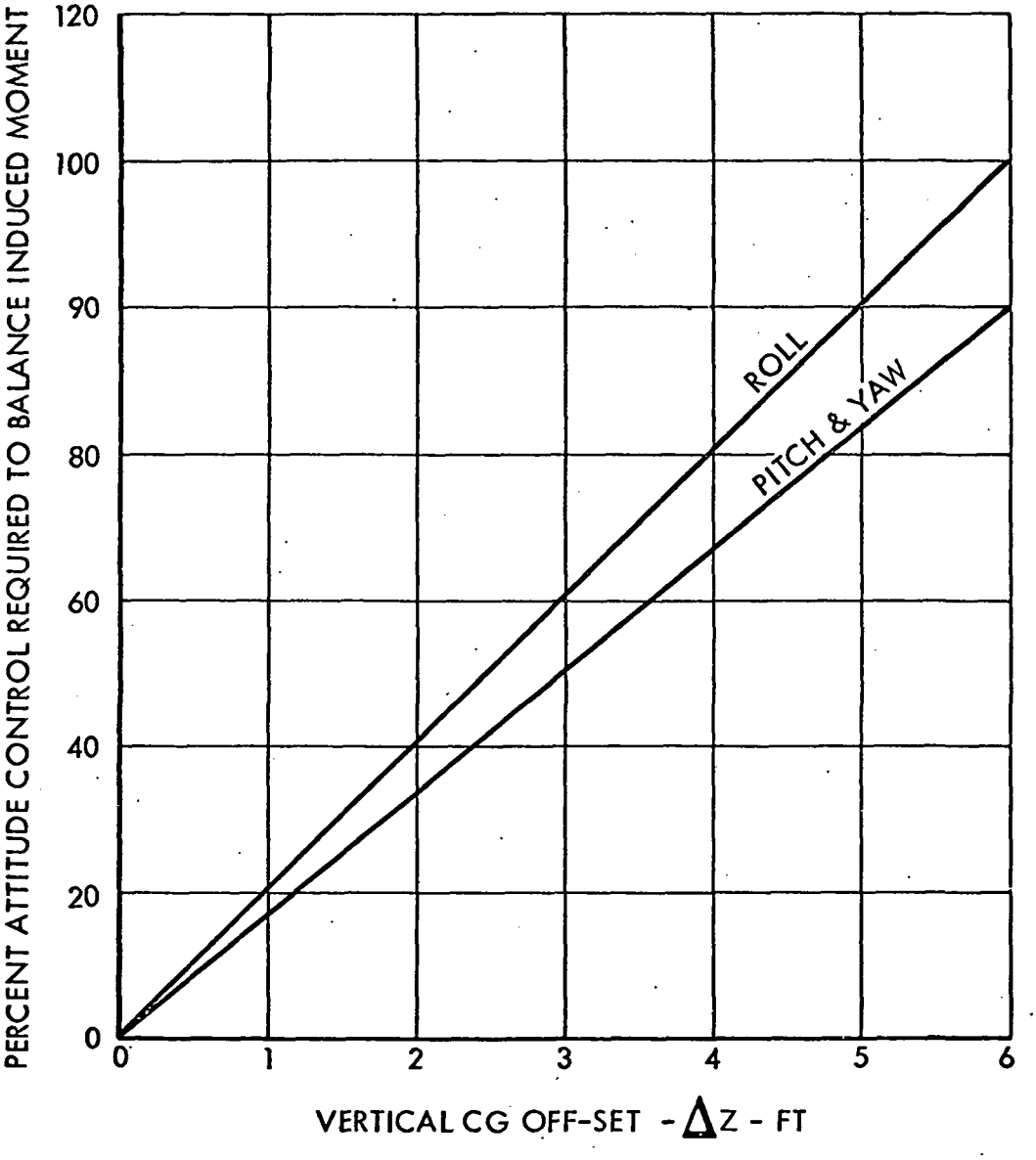


Figure 28

CROSS-COUPLING EFFECTS

ASYMMETRIC THRUST

ACCELERATION COMMAND

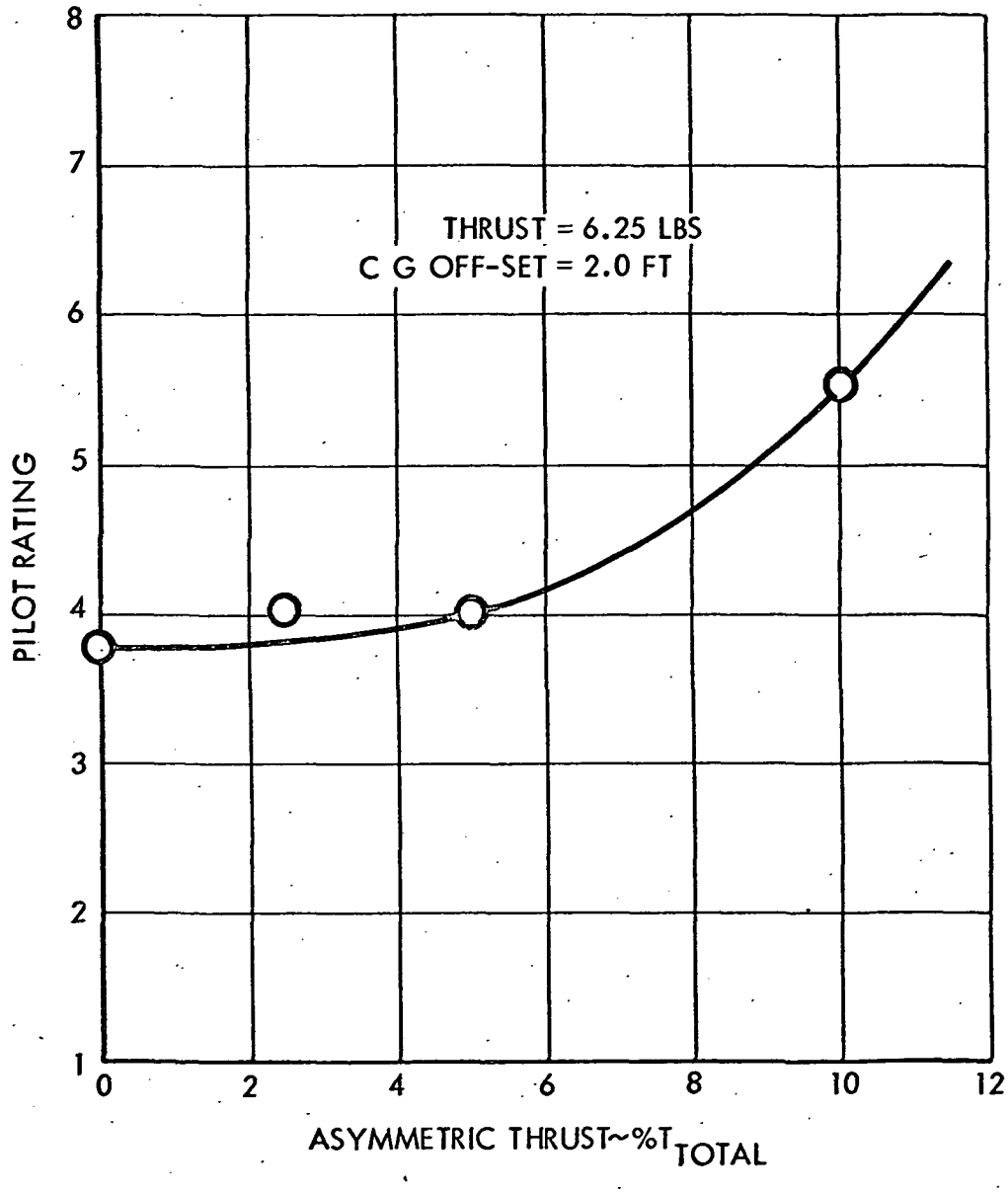


Figure 29

CROSS - COUPLING EFFECTS

ASYMMETRIC THRUST

RATE COMMAND

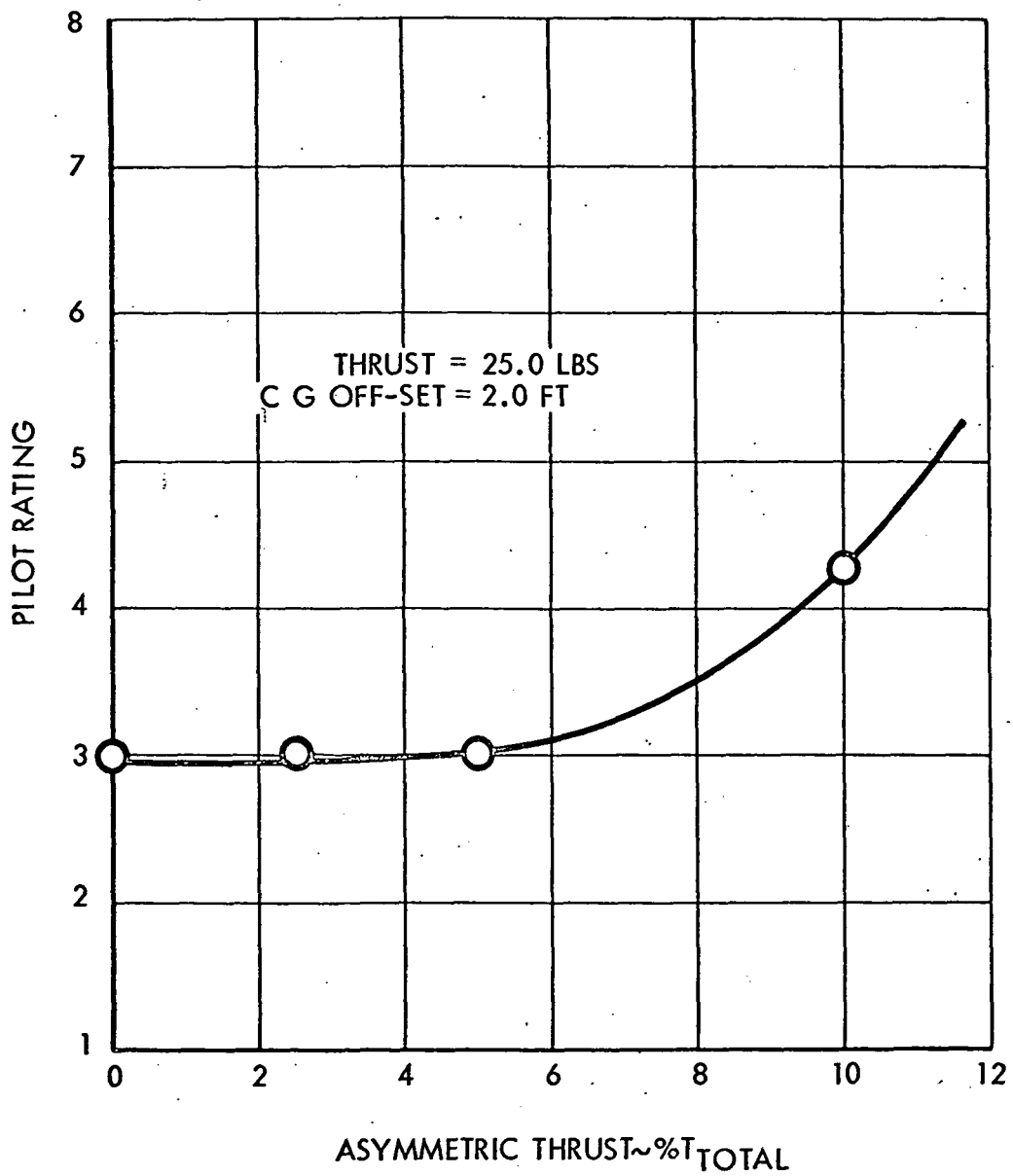


Figure 30

CROSS-COUPLING EFFECTS-

ASYMMETRIC THRUST

RATE COMMAND ATTITUDE-HOLD

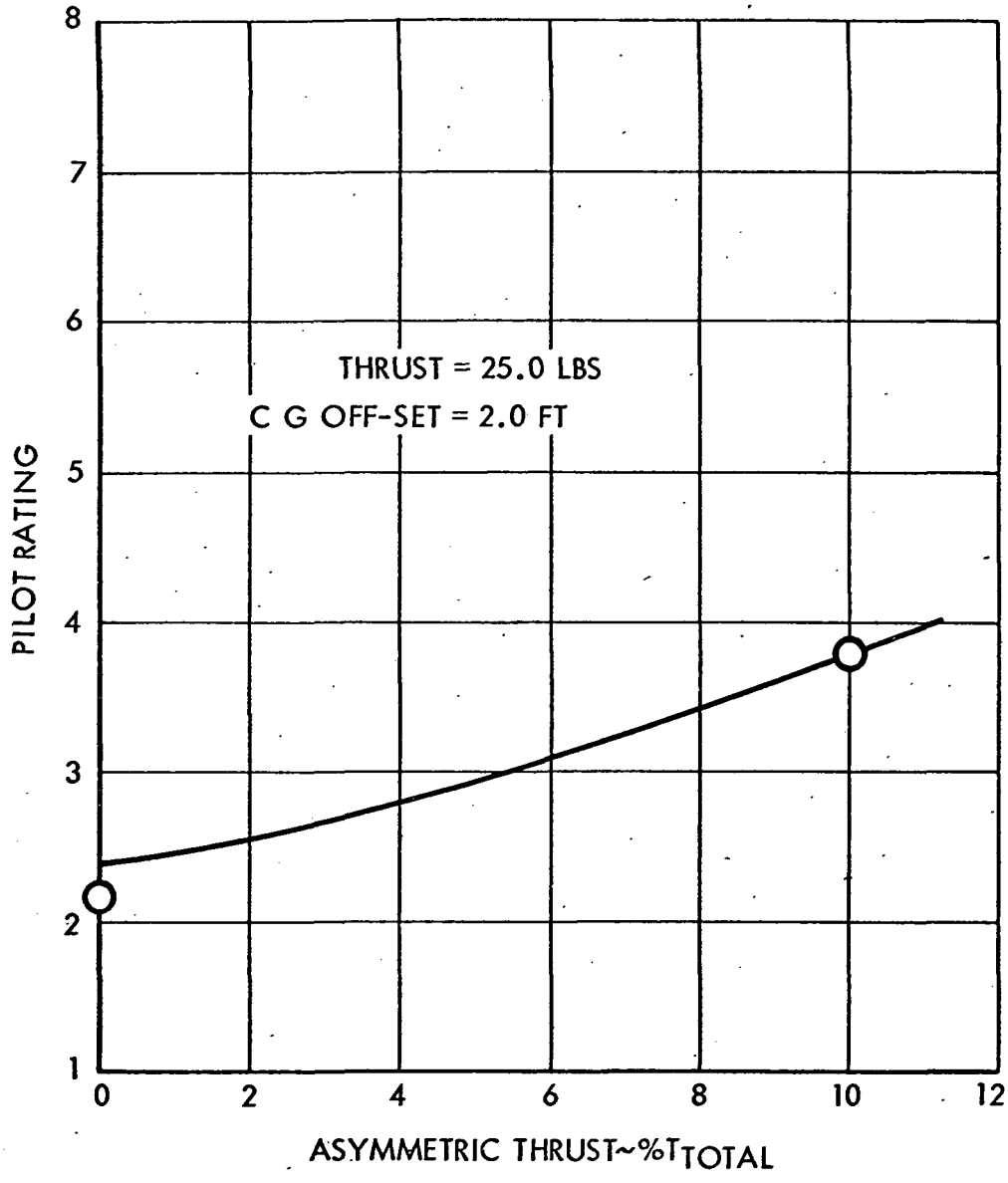


Figure 31

VISUAL AIDS

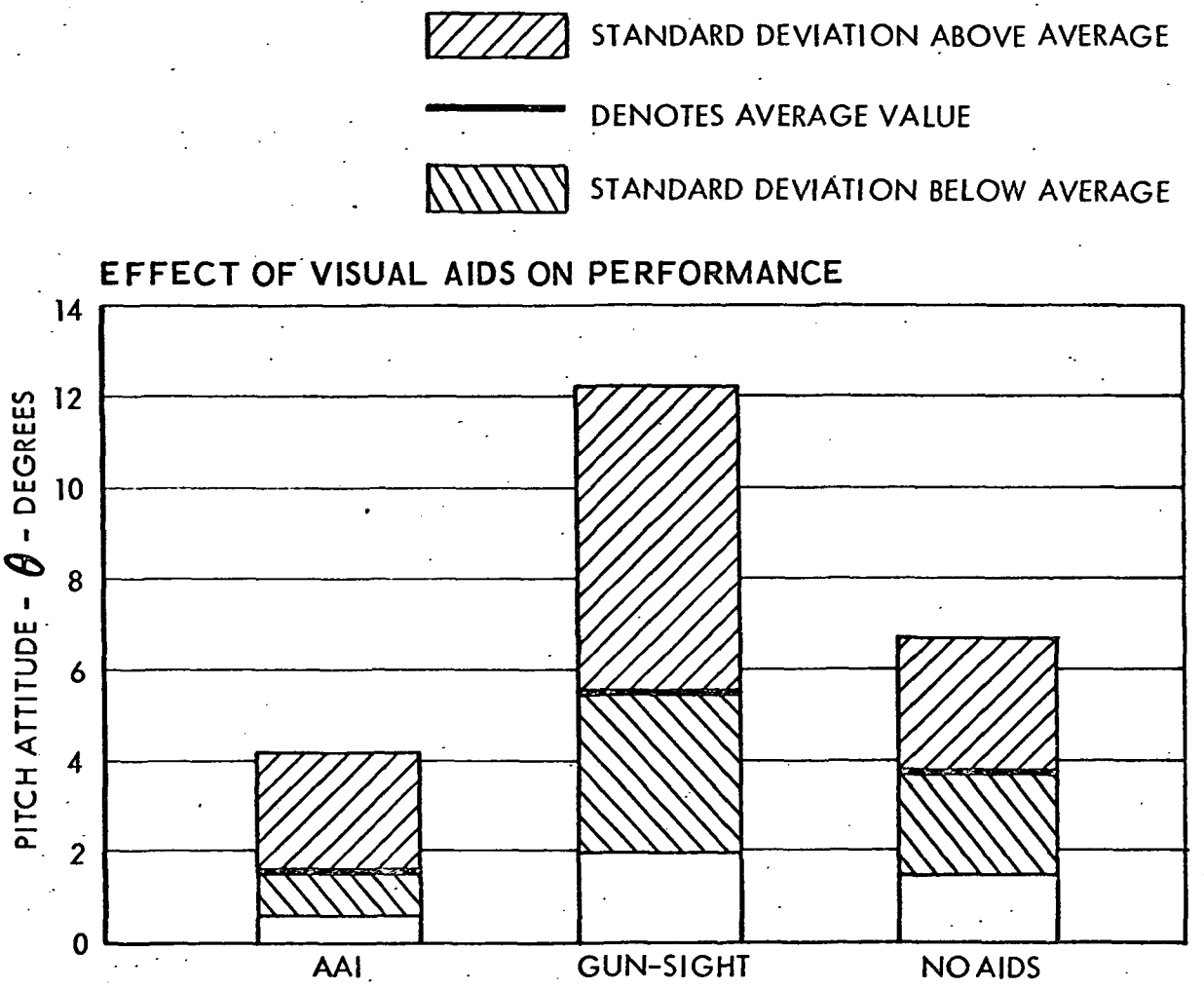


Figure 32

VISUAL AIDS

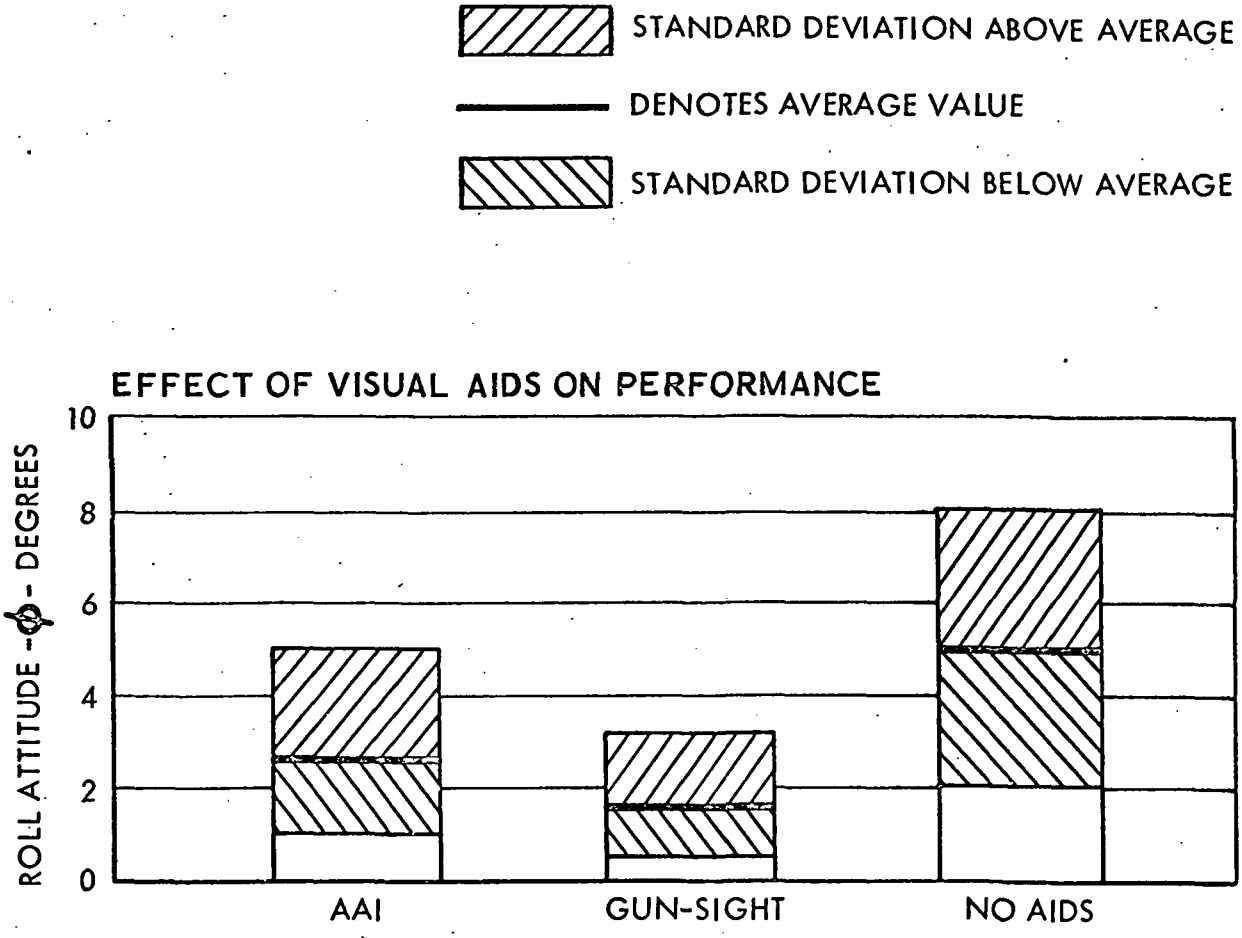
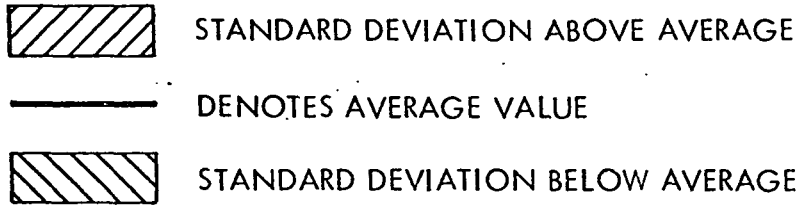


Figure 33

PAGE MISSING FROM AVAILABLE VERSION

VISUAL AIDS



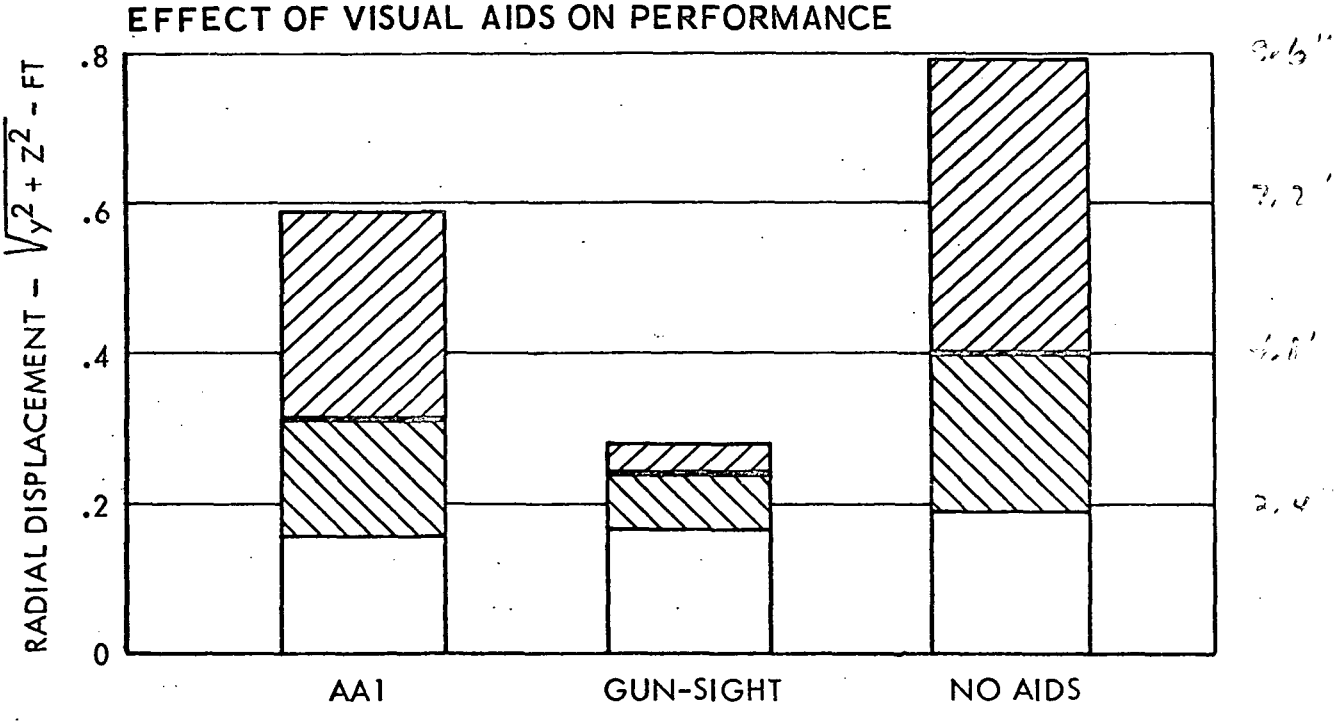


Figure 35

SYSTEM PERFORMANCE

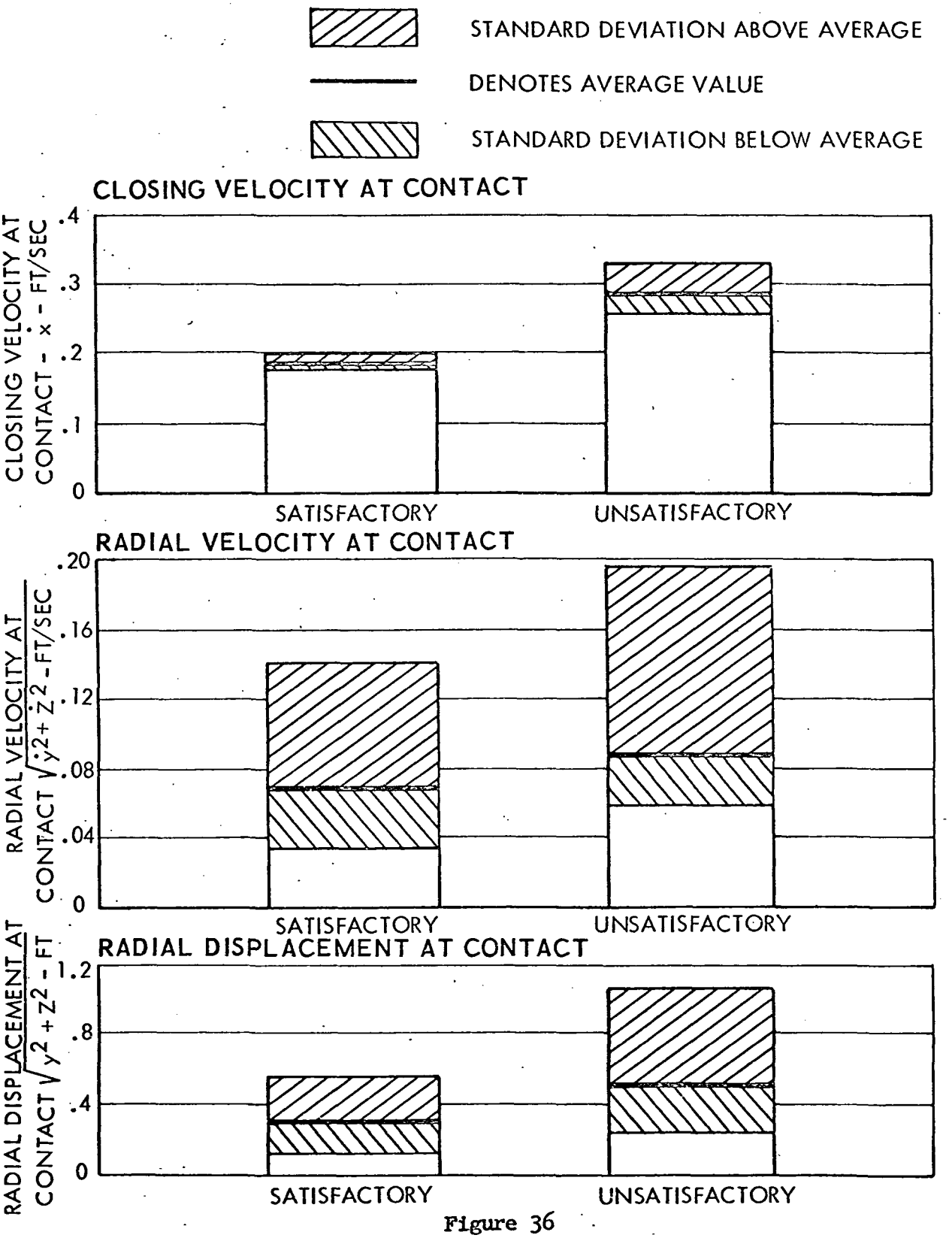


Figure 36

SYSTEM PERFORMANCE

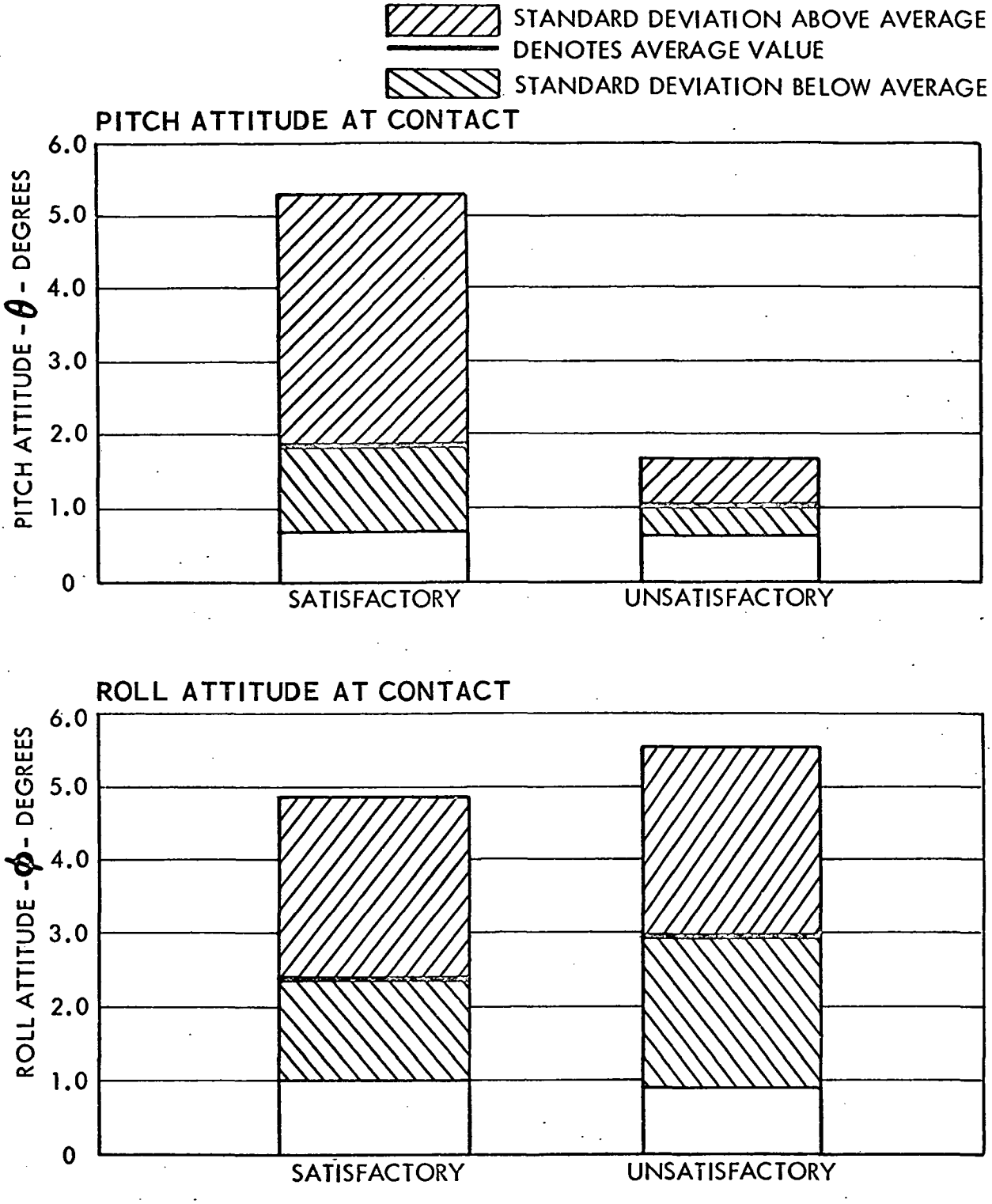


Figure 37

SYSTEM PERFORMANCE

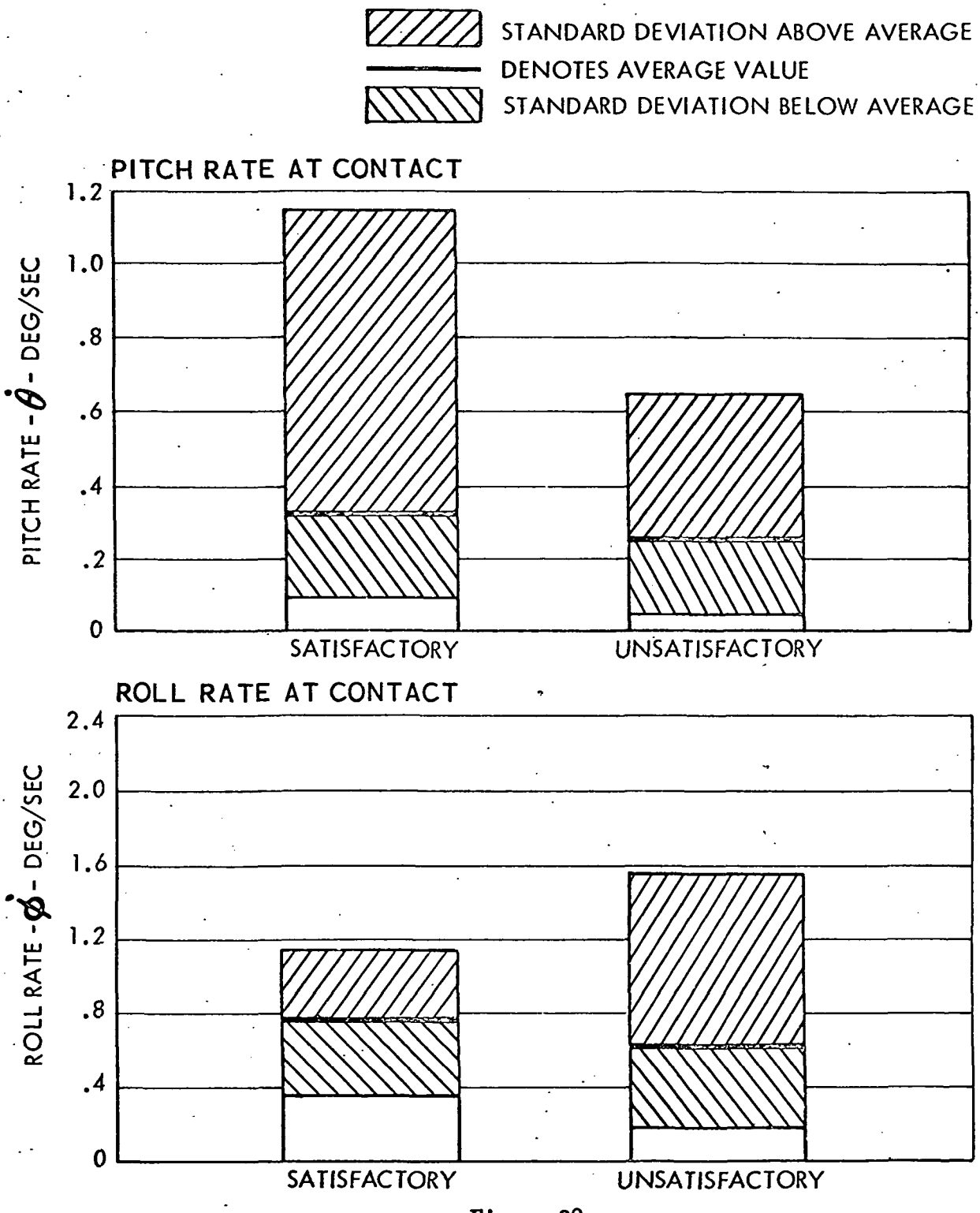


Figure 38

APPENDIX A

EQUATIONS OF MOTION

$$\dot{p} = \frac{1}{I_{xx}}\left[2T_\phi \ell_\phi + 2T_Y \Delta Z - 2T_Z \Delta Y\right]$$

$$\dot{q} = \frac{1}{I_{YY}}\left[2T_\theta \ell_\theta + 2T_Z \Delta X - 2T_X \Delta Z - (I_{xx} - I_{zz}) pr\right]$$

$$\dot{r} = \frac{1}{I_{zz}}\left[2T_\psi \ell_\psi + 2T_X \Delta Y - 2T_Y \Delta X - (I_{YY} - I_{xx}) pq\right]$$

$$\dot{\phi} = p + r\theta$$

$$\dot{\theta} = q - r\phi$$

$$\dot{\psi} = r + q\phi$$

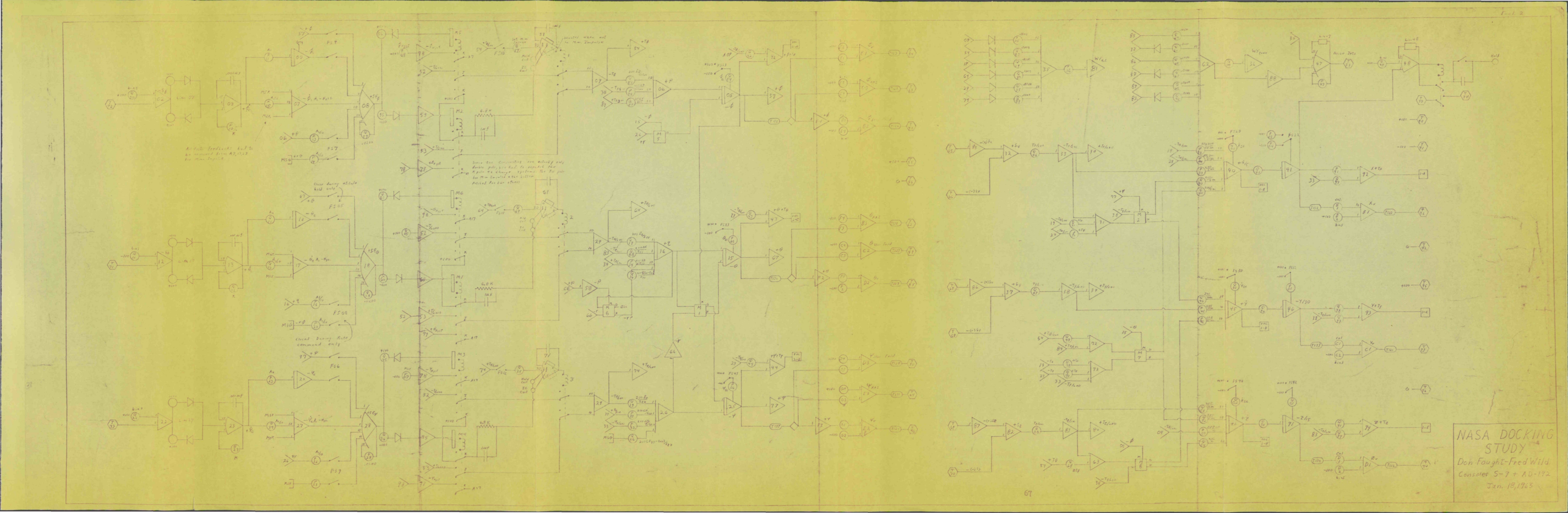
$$\ddot{X} = \frac{1}{m}\left[2T_X + \Delta T_\theta + \Delta T_\psi - 2T_Y \psi + (2T_Z + \Delta T_\phi)\theta\right]$$

$$\ddot{Y} = \frac{1}{m}\left[(2T_X + \Delta T_\theta - \Delta T_\psi)\psi + 2T_Y - (2T_Z - \Delta T_\phi)\phi\right]$$

$$\ddot{Z} = \frac{1}{m}\left[-(2T_X + \Delta T_\theta + \Delta T_\psi)\theta + 2T_Y \phi + 2T_Z + \Delta T_\phi\right]$$

$$WF_{ROT} = \frac{2}{I_{sp}}\int(|T_\phi| + |T_\theta| + |T_\psi|)\,dt$$

$$WF_{TRANS} = \frac{2}{I_{sp}}\int(|T_x| + |T_Y| + |T_Z|)\,dt$$


NASA DOCKING STUDY
Doh Faught-Fred Wild
Consoles S-7 + AD-172
Jan. 18, 1963